Quarterly Publication

ISSN 2383 - 3572

Global Journal of Environmental Science and Management

Volume 11, Number 2, Spring 2025

Global Journal of Environmental Science and Management (GJESM)

(QUARTERLY PUBLICATION)

Publisher and Editor-in-Chief
Professor J. Nouri
GJESM Publisher INC, USA
Email: nourijafar@gmail.com
gjesm.publication@gmail.com

Managing Editor
Professor D. Sivakumar
Kalasalingam Academy of Research and Education, Tamil Nadu, India
Email: sivakumar.gjesm@gmail.com

Technical Editor
Professor M. Samimi
Kermanshah University of Technology, Kermanshah, Iran
Email: m.samimi@kut.ac.ir

Assistant Editor
Dr. S.M. Tehrani
International Journal of Human Capital in Urban Management
Email: tehranishohre@gmail.com

Page Designer
A. Rezaye Soltanabadi
Imajgaran Danesh

Editorial Contact Information
621 W. Chapman Ave, Orange, CA 92868
USA
Phone: +1(949)405 0540
Email: gjesm.publication@gmail.com
editor@gjesm.net

Website: https://www.gjesm.net/
https://www.gjesm.com/

Publication Center
GJESM Publisher INC.
publisher@gjesm.net
gjesm.publication@gmail.com

Editorial Board

Professor V.K. Gupta; *University of Johannesburg,* ***South Africa***

Professor M. Sillanpää; *Lappeenranta University of Technology,* ***Finland***

Professor A. Fauzi Ismail; *Universiti Technologi Malaysia,* ***Malaysia***

Professor A.T. Peterson; *University of Kansas,* ***USA***

Professor A. Cerda; *University of Valencia,* ***Spain***

Professor J.-D. Gu; *University of Hong Kong,* ***P.R. China***

Professor S.I. Allakhverdiev; *Russian Academy of Sciences,* ***Russia***

Professor D. Wen; *University of Leeds,* ***UK***

Professor T. Yigitcanlar; *Queensland University of Technology,* ***Australia***

Professor A. Z. Aris, *Universiti Putra Malaysia,* ***Malaysia***

Professor K. Yetilmezsoy, *Yildiz Technical University,* ***Turkey***

Professor K.E. Noll; *Illinois Institute of Technology,* ***USA***

Professor J. Nouri; *Tehran University of Medical Sciences,* ***Iran***

Professor D. Sivakumar; *Kalasalingam Academy of Research and Education,* ***India***

Professor J. Aravind; *Saveetha Institute of Medical and Technical Sciences,* ***India***

GJESM is licensed under a "Creative Commons Attribution 4.0 International (CC-BY 4.0)"
Publication authorization is certified by the Ministry of Culture and Islamic Guidance, No. 93/3629; 14 May 2014
Scientific-Research grade is accredited by the Ministry of Science, Research and Technology; No. 3/18/59975; 20 June 2015

Let s work together to publish the knowledge
and science to serve better the environment

Circulation: 500

***p*ISSN 2383 - 3572** ***e*ISSN 2383 - 3866**

Aims and Scope

Global Journal of Environmental Science and Management (GJESM) is an international scholarly refereed research journal which aims to promote the theory and practice of environmental science and management. A broad outline of the journal's scope includes; peer reviewed original research articles, case and technical reports, reviews and analyses papers, short communications and notes to the editor, in interdisciplinary information on the practice and status of research in environmental science and management, both natural and man-made. The main aspects of research areas include, but are not exclusive to; environmental chemistry and biology, environments pollution control and monitoring, transport and fate of pollutants in the environment, concentrations and dispersion and trace of wastes in air, water, and soil, point and non-point sources pollution, heavy metals and organic compounds in the environment, atmospheric pollutants and trace gases, solid and hazardous waste management; soil biodegradation and bioremediation of contaminated sites; environmental impact assessment, industrial ecology, ecological and human risk assessment; improved energy management and auditing efficiency and environmental standards and criteria.

Vision and Mission

Global Journal of Environmental Science and Management (GJESM) publishes original. Peer-reviewed and technical environmental articles serve those environmental science and management through the on time quarterly publication with reliable information. GJESM is an integral partner with the scientific and technical communities, delivering superior information products and services that foster communication, build insights and enables individual and collective advancement in environmental research. Providing environmental science and management information to the general public with descriptions of contemporary advances in environmental issues to be used in improving environmental protection and management.

Abstracting and Indexing

Web of Science (ESCI); Scopus; Scimago Journal Rank (SJR); ProQuest (Agricultural and Environmental Science + Natural Science Collection + Ulrichsweb); Chemical Abstract (CAS); CABI Abstract; Global Health Abstract; Agricola; Committee on Publication Ethics (COPE); PubMed-NCBI; DOAJ; Open J-Gate; Google Scholar; Academia.edu; Geomar; WorldCat; Academic Resource Index; Environmental XPRT; Information Matrix for the Analysis of Journals (MIAR); Bibliothek Humburg; ScienceMedia; JournalTOCs; MSRT; ISC; RICeST; SID; Civilica; Magiran.

Serial # 42

Global Journal of Environmental Science and Management
GJESM

Publisher and Editor-in-Chief
Professor J. Nouri

eISSN 2383 3866
pISSN 2383 3572

Quarterly Full Open Access Peer Reviewed Publication

Journal Abbreviation: Global J. Environ. Sci. Manage.



CALL FOR PAPERS

Publication benefits in GJESM Journal

- *Online Publication Journal*
- *Online Submission and Reviewing*
- *Online Status Inquiry*
- *Double Blind Review*
- *Fast-Track Review and Publication*
- *Immediate Publication on the Net*
- *Article Podcasts Implementation*
- *Indexed in Scopus Database with CiteScore = **7.9***
- *Scopus Percentile (WORLD TOP-TEN: 95th in Social Science)*
- *Scopus **Q1** Category*
- *Indexed in Web of Science Database with **IF = 3.1***
- *Web of Science JCR with **Q2** Category*

Indexed by Scopus

Clarivate Web of Science™ Core Collection ESCI Journals

Journal Citation Reports 2023 Clarivate Analytics 3.1

Journal Website:
https://www.gjesm.net
https://www.gjesm.com

Email:
gjesm.publication@gmail.com

Phone:
+1(949)405 4538
+1(949)405 0540

Address: 623 W. Chapman Ave, Orange, CA 92868 USA

Better Environment is Our Prime Concern

Global
Journal of Environmental Science and Management

CONTENTS

Volume 11, Issue 2, Spring 2025

Removal of trihalomethanes from activated Napier grass-derived adsorbent using liquefied gas and chemical pretreatment **(365 - 390)**

S. Sriboonnak; A. Wongrueng; P. Rakruam; S. Nitayavardhana; P. Sittisom; A. Siyasukh; P. Induvesa; B. Sawangjang; S. Takizawa (INDONESIA)

Optimized removal of trivalent arsenic from aquatic environments using Prosopis juliflora seed biomass **(391 - 402)**

M. Samimi; J. Nouri (IRAN/ USA)

Projection of future temperature variations in river basins under climate change scenarios using general circulation models **(403 - 426)**

H.A. Hroub; M. Rahbeh; M.M. Zoubi; Q.Y. Abu-Afifeh; H. Al-Jawaldeh; N. Obeidat (JORDAN)

Dynamics prediction of land use changes using cellular automata and artificial neural network modeling **(427 - 442)**

S.S.B. Girsang; D.M. Banurea; P. Lestari; J.B. Nambela; I. Verawaty; J. Barus; Jonharnas ,; M.A. Girsang; T. Purba (INDONESIA)

Eco-friendly biocontrol of Phytophthora capsici in black pepper (Piper nigrum) using Burkholderia species **(443 - 460)**

Sukamto ,; K.D. Sutanto; R. Noveriza; S. Hardiyanti; Wiratno ,; S.R. Djiwanti; D. Manohara; I.B. Rahardjo; R. Harni; W. Amaria; Supriadi (INDONESIA)

Spatial heterogeneity of marine debris distribution on a tropical remote island shoreline **(461 - 480)**

D. Purnama; N.P. Zamani; D.G. Bengen; R. Saville; M.R. Cordova (INDONESIA/ JAPAN)

Optimizing industrial and domestic water consumption efficiency for sustainable growth through data envelopment analysis **(481 - 496)**

Z. Bayat; J. Vives Costa; J.J. de Felipe Blanch (SPAIN)

Innovation in the blue economy and environmental sustainability in marine and fisheries strategy **(497 – 518)**

S.W. Trenggono; I. Meilano; H. Latief; S.D. Diantara; W. Sakti; D.G.K. Ketaren; I.N.P. Winata; T. Yuwono; Syamdidi ,; F.Y. Arthatiani; K. Kasim; I.N. Radiarta (INDONESIA)

Social acceptance of water quality through decentralized greywater treatment using green wall system **(519 - 532)**

N. Obeidat; A. Abu-Awwad; A.S. Al-Salaymeh; J. AlBtoosh; M.M. Zoubi; Q.Y. Abu-Afifeh; M.A. Seif; H. Hroub; O. Arabiat (JORDAN/ AUSTRALIA)

Modeling the effects of land use change on agricultural carrying capacity and food security **(533 - 554)**

R. Harini; R. Rijanta; E.H. Pangaribowo; R.F. Putri; I. Sukri (INDONESIA)

Balancing environmental quality and economic profitability for sustainable rice-soybean cropping system **(555 – 572)**

B. Phrommarat; N. Phrommarat (THAILAND)

The impacts of land use and cover change on water quality of watershed basin (573 - 592)

D.P. Marisi; Suprihatin; S. Hariyadi; R.L. Kaswanto (INDONESIA)

Hydrodynamic simulation experiment of tidal pump in strait waters (593 - 608)

W.S. Pranowo; K. Malik; D. Adrianto; A. Kurniawan (INDONESIA)

Ecological features of mangroves as indicators of seawater intrusion (609 - 630)

Suyadi ,; M. Basyuni; R. Amukti; C. Damayanti; D. Stokes; A. Mubaraq; Y.I. Rahmila (INDONESIA)

Ecological population dynamics, host preferences, and associated parasitoids of Bactrocera carambolae and Bactrocera papaya on fruits (631 - 652)

D. Koswanudin; H. Widyanto; D. Hutapea; Wawan; R. Yuniawati; V.N.O. Subagyo; S. Utami; I.M. Samudra; W. Darwiati (INDONESIA)

Sesbania grandiflora activated carbon as a high-efficiency stable and reusable adsorbent for sustainable fluoride removal (653 - 676)

D. Sivakumar; M Perarul Selvan; J. Nouri; M. Juhi Jabin; S. Priyanka; G. Madhubala (INDIA/ USA)

A model designed for estimating biomass and carbon pool stock in over-mature plantations of teak; Tectona grandis (677 - 694)

C.A. Siregar; B.H. Narendra; I.K. Abywijaya; P. Pratiwi; L. Alhamd; I.W.S. Dharmawan; E.E.W. Hadi; H. Kurniawan (INDONESIA)

Reducing hydrogen consumption in hybrid electric vehicles using aquila optimization algorithm (695 - 710)

A.M. Nassef. H.E. Ghadbane. E.T. Saved . H. Rezk (SAUDI ARABIA/ ALGERIA/ EGYPT)

Morphological and molecular monitoring of fishes in the waters of mangrove ecosystems (711 - 732)

M. Basyuni; Irmawati ,; A. Mubaraq; A. Susilowati; A.B. Rangkuti; Desrita ,; A.A. Aznawi; S.S. Al Mustaniroh; S.H. Larekeng; A.H. Salman; E.R. Ardli; Y. Isowa; T. Kajita (INDONESIA)

Sustainable pest management with citronella oil for eco-friendly control of Aphis gossypii in chili plants (733 - 746)

M. Istianto; K.D. Sutanto; S. Ikawati; R.C. Wicaksono; S. Widyaningsih; M.E. Dwiastuti; U. Triasih; O. Endarto; Affandi; Handoko I. Yustina; L. Mufidah; S. Wuryantini; Nurjanani; S. Agustini; D. Setyorini; D.W. Utami (INDONESIA)

Multi-dimensional perspectives on sustainability in domestic waste management (747 - 770)

Y. Ismail, R. Adji, A.D. Santoso, S. Wahyono, M.A. Kholiq, T. Handayani, S.D.R. Pahri, S. Putiamini, R.A. Pratama, F. Nurfatriani, F.L. Sahwan, F. Suryanto, Prasetiyadi, R.D. Tilottama (INDONESIA)

The impact of land use change on morphological and anatomical adaptations of Rhizophora species (771 - 790)

A.B. Rangkuti; P. Peniwidiyanti; M. Basyuni; D. Elfiati; A. Susilowati; A. Mubaraq; M.R. Hariri; A.P. Dewi; F. Indriani; F.G. Dwiyanti; B. Slamet; K.S. Hartini; R.A. Syahputra (INDONESIA)

Green chemistry approach to formaldehyde detection using fish albumin-modified gold electrodes (791 - 804)

T.P.H. Hutapea; Suprapto ,; M.Y. Syahputra; F. Kurniawan (INDONESIA/ JAPAN)

Mathematical model of the territorial bioecological coefficient to evaluate the progress of the sustainable development goal (805 - 824)

R. Zapata Stacey; D. Pinto Osorio; C.A. Rodríguez Nieto; M. Machado Penso (COLOMBIA)

A global perspective on sustainable pathways for biogas adoption (825 - 856)

K. Biró; K.S. Woon; W. Ounsaneha; C. Rattanapan (THAILAND/ MALASIA/ CHINA)

Global J. Environ. Sci. Manage. 11(2): 365-390, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Removal of trihalomethanes from activated Napier grass-derived adsorbent using liquefied gas and chemical pretreatment

S. Sriboonnak[1], A. Wongrueng[1,*], P. Rakruam[1], S. Nitayavardhan[1], P. Sittisom[1], A. Siyasukh[2], P. Induvesa[3], B. Sawangjang[4], S. Takizawa[4]

[1]Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, 50200, Thailand
[2]Department of Industrial Chemistry, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand
[3]Department of Environmental science, Faculty of Science, Silpakorn University, Nakhon Pathom 73000, Thailand
[4]Department of Urban Engineering, Graduate School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan

ARTICLE INFO

Article History:
Received 26 October 2024
Revised 29 December 2024
Accepted 03 February 2025

Keywords:
Adsorbent
Adsorption
Chemical pretreatment
Liquefied petroleum gas
Napier grass
Trihalomethane

DOI: 10.22034/gjesm.2025.02.01

ABSTRACT

BACKGROUND AND OBJECTIVES: Disinfection by-products in water treatment result from the reaction of disinfectants with organic and inorganic precursors, mostly dissolved organic matter. Trihalomethanes, a key category of disinfection byproducts, are regarded as probable carcinogens. Public health organizations such as World Health Organization and United States Environmental Protection Agency have set maximum allowed concentrations for trihalomethanes in drinking water. A range of techniques, notably adsorption, is utilized to address the removal of trihalomethane precursors, where activated carbon has shown effectiveness, though it comes at a high price. This study investigates the use of low cost materials, namely Napier grass, for the production of adsorbents by pyrolysis, with the objective to enhance efficiency and reduce expenses in the removal of trihalomethanes. The current study analyzed multiple variables, including chemical pretreatment, particle dimensions, contact time, and concentration levels, to determine the performance of the adsorbent in relation to trihalomethanes. The purpose of this study is to utilize of low-cost materials, specifically Napier grass, for the production of adsorbents through pyrolysis. Furthermore, this study focuses on enhancing efficiency and lower the expenses associated with the elimination of trihalomethanes.
METHODS: The application of chemical pretreatments with sodium hydroxide, phosphoric acid, and ferric nitrate resulted in the generation of an adsorbent obtained from Napier grass. An analysis of the percentage elimination of trihalomethanes alongside the porous characteristics of the synthesized adsorbent was performed to ascertain the viability of employing liquefied petroleum gas as a combustion source in the pyrolysis process. The activation duration of 1 hour at 600 degrees Celsius was used to measure the maximum Brunauer–Emmett–Teller surface area and micropore volume of the adsorbent. The analysis of pore structure through the nitrogen adsorption-desorption technique indicated a greater presence of micropores in comparison to mesopores. Adsorbent characterizations were conducted using scanning electron microscopy with energy-dispersive x-ray spectroscopy, and X-ray diffraction. The burn-off percentage, removal effectiveness of trihalomethanes, and the kinetics and isotherm adsorption on the adsorbent generated from Napier grass were analyzed. This study analyzed the trihalomethane species including chloroform, bromodichloromethane, dibromochloromethane, and bromoform.
FINDINGS: The adsorbent derived from Napier grass, after being pretreated with phosphoric acid at a dosage of 3.0 grams per liter, achieved a maximum trihalomethane removal rate of 94.43 percent. The pseudo-second order kinetic model (correlation coefficient values=0.982, p-value<0.05) fits with the adsorption kinetics of trihalomethanes on Napier grass-derived adsorbents were pretreatment with phosphoric acid, proving a maximum adsorption capacity of 220.2 micrograms per gram. In addition, pore diffusion is a key element in managing the adsorption dynamics of trihalomethane substances. The main process of absorption is physical absorption, as indicated by the free adsorption energy.
CONCLUSION: The use of an adsorbent derived from Napier grass for the removal of trihalomethanes demonstrated an environmentally friendly, cost-effective, and efficient approach, indicating its potential application in water treatment processes.

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
78

NUMBER OF FIGURES
8

NUMBER OF TABLES
5

*Corresponding Author:
Email: *aunnop@eng.cmu.ac.th*
Phone: +665 3944 192
ORCID: 0000-0001-9180-3949

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Disinfection by-products (DBPs) in water treatment processes are generated from precursors reacting with disinfectants, such as chorine, chloramines, ozone, and chlorine dioxide (Chen *et al.*, 2007; Lu *et al.*, 2020). There are both organic and inorganic precursors. A segment of dissolved organic matter (DOM), including humic and fulvic substances (Thokchom *et al.*, 2020), constitutes the organic precursors, which are the principal components of natural organic matter. On the other hand, inorganic precursors include elements like chlorine, bromine, and iodine (Nakanishi, 2006; Dong *et al.*, 2019). DOM in raw water to water supply systems is the major problem of DBPs in treated water. Trihalomethanes (THMs), haloacetic acids (HAAs), and haloacetonitriles (HANs) are the main types of DBPs (Thokchom *et al.*, 2020; Office of Water, 2016; Plewa *et al.*, 2007). These DBPs are genetically toxic and cytotoxic (Tugulea *et al.*, 2017; Hong *et al.*, 2017). THMs, which consist of chloroform (CF), bromodichloromethane (BDCM), dibromochloromethane (DBCM), and bromoform (BF), were previously identified as potential carcinogens for humans. They were firstly detected in drinking water in 1974 (Rook, 1974). The World Health Organization (WHO) set the allowable limit for total THMs at 100 micrograms per liter (µg/L) (World Health Organization, 2011) According to the United States Environmental Protection Agency (USEPA), the permissible level of total trihalomethanes (THMs) contamination is set. The concentrations of CF, BDCM, DBCM, and BF in Thailand are 300, 60, and 100 µg/L, respectively, following the World Health Organization's guidelines. Rook (1974) reported that the DBPs such as THMs are generated from reactions between DOM and chlorine. Sriboonnak *et al.* (2021) found the presence of THM species in treated water sourced from the reservoir and within the water supply system. The production of THMs occurred naturally, with their concentrations arising from the use of chlorine dioxide disinfection. The specific ultraviolet absorbance (SUVA) value of raw water exceeds 2 liters per milligram per meter (L/mg/m), indicating that the majority of organic compounds are characterized by an abundance of double bonds. Chlorine reactions during disinfection processes produce chemicals that serve as precursors to DBPs, such as THMs. In the raw surface water, the concentration of total THMs was approximately 60 µg/L, while in the water supply system, it measured about 170 µg/L (Sriboonnak *et al.*, 2021). Ali *et al.* (2019) detected the THMs in a surface-water treatment facility in Uganda, with concentrations ranging from 59 to 85 µg/L, and observed that the concentration of total THMs increased during the dry season at 636.8 µg/L than the rainy season at 430.1 µg/L (Poleneni, 2020; Kearns *et al.*, 2015). The THMs were dominated by the species CF, whereas the HANs were found to be mostly composed of trichloroacetonitriles (Ratpukdi *et al.*, 2019). Furthermore, THMs present in drinking water in France and USA range from 64 to 622 µg/L and 90 to 370 µg/L, repectively (Manasfi *et al.*, 2017; Kralles *et al.*, 2020). Several studies have focused on the removal of THM precursors using techniques like photolysis, ozonation, adsorption, and the synergistic integration of these methods (Park *et al.*, 2014; Deeudomwongsa *et al.*, 2017; Khan *et al.*, 2020). Each of these methods possesses distinct advantages and disadvantages. Adsorption is a widely used technique in several countries for multiple applications. Activated carbon adsorption is considered an effective method for the removal of natural organic matter (Zhoa *et al.*, 2024; Bond *et al.*, 2009), owing to its efficiency, convenience, and cost-effectiveness in eliminating micropollutants (Matsui *et al.*, 2015). The porous structure of the adsorbent, shaped by the choice of materials and the pretreatment processes, leads to its significant surface area and porosity. Although various adsorbents are used for gas separation (Wang *et al.*, 2021; Song *et al.*, 2013) and micro-pollutant removal, their costs are high such as commercially available activated carbon (AC) produced from coal. Consequently, there is a heightened attention towards cost-effective materials. Some of the reported low-cost adsorbents were produced from local materials such as corncobs, bamboo, rubber wood sawdust, cotton, and fabric (Liu *et al.*, 2020; Liu *et al.*, 2014; Mazlan *et al.*, 2016; Ren *et al.*, 2023; Yimyam *et al.*, 2023). Elephant grass (*Pennisetum purpureum* Schum), also known as Napier grass, is used as forage for livestock. Recognized for its rapid growth and high abundance, this resource holds considerable potential as a renewable source for simple and economical adsorbents (Da Silva Veiga *et al.*, 2020). Additionally, it can be converted into biochar via pyrolysis (Reza *et al.*, 2019; Meyer *et al.*, 2011). The utilization of

agricultural waste presents an opportunity to enhance value rather than disposing of it through incineration, which leads to a greater volume of waste compared to a combustion system that includes the use of all waste components. Energy crops provide an alternative means of sourcing raw materials for charcoal manufacturing. The biomass derived from these plants is classified as carbon neutral (Nantasaksiri *et al.,* 2021). The material utilized at the conclusion of the absorption process is eligible for recycling. The methods to produce adsorbents commonly consist of two steps: 1) charcoal production, i.e., pyrolysis, and 2) activation. In the pyrolysis step, the carbon contents of raw materials increase. This stage is accomplished by applying heat to the raw material, which facilitates the evaporation of volatile elements from its structure. Activation can occur through two primary techniques physical and chemical. In the physical processes, the raw materials are stimulated by oxidizing gas at 400–1000 degrees Celsius (°C), and commonly used oxidizing gases are steam, nitrogen gas (N_2), and carbon dioxide (CO_2). This process is designed to increase the porosity and surface area of the materials. Nonetheless, it is crucial to understand that it demands a considerable amount of energy. Conventional pyrolysis using synthesis gases like N_2 and CO_2 at temperatures in the range of 400-600°C produces the post-combustion products: biochar, waste gas, and bio-oil. Bridgwater (2012) indicated that the yields of biochar, waste gas, and bio-oil recovered following pyrolysis with N_2 were 35 percent (%), 35%, and 30%, respectively. Consistent with the findings of Mohammed *et al.* (2016c), the charcoal yield ranged from 15 to 25%, gas from 20 to 30%, and bio-oil from 40 to 60%. However, Ifa (2020) found that the charcoal production generates less waste gas, 19.7%, with a charcoal content of 41% and performed pyrolysis using liquefied petroleum gas (LPG). This approach results in a smaller volume of waste gas when contrasted with combustion involving synthesis gas. The aim of this study was to employ LPG as a heating medium during the pyrolysis process for the creation of charcoal. To reduce the costs entailed by synthetic gas, which exceeds the cost of conventional cooking gas, the combustion temperature is set at 600°C. The chemical process is a carbon-based chemical reaction, such as zinc chloride ($ZnCl_2$), phosphoric acid (H_3PO_4), sodium hydroxide (NaOH), ferric chloride ($FeCl_3$), and ferric nitrate ($Fe(NO_3)_3$ (Yimyam *et al.,* 2023). Prior to activation at temperatures of 650 to 800°C, the pyrolyzed agricultural waste was chemically treated with NaOH. This process produced AC with extremely large surface areas, measuring 123–3014 square meter per gram (m^2/g) (Ahmedna *et al.,* 2004; Premchand *et al.,* 2024). NaOH The process involved subsequent H_3PO_4 impregnation and activation at high temperatures ranging from 200 to 700°C. AC was generated, exhibiting a surface area of 676.8 m^2/g (Fan *et al.,* 2024). This acid plays a crucial role in the breakdown, removal of water, and reconfiguration of biopolymers. Additionally, these processes contribute to the transformation of aliphatic compounds into aromatic structures, which increases the yield of adsorbent (Teng *et al.,* 1998). According to Siyasukh *et al.* (2018), pretreatment with $Fe(NO_3)_3$, similar to adsorbent preparation, creates the surface porous and enhances absorption efficiency. In addition, the alkaline additive (NaOH) reduced the decomposition temperature of wood and increased the biochar yield. This indicates that the alkali engages with biomass, converting specific organic compounds into inorganic forms that are removed during the pretreatment phase (Di Blasi *et al.,* 2009). The impregnations promote carbonization efficiency, thereby assisting in the creation of the required pore structures (Siyasukh *et al.,* 2018; Xu *et al.,* 2019). Compared to the physical method, the chemical method provides notable advantages, including lower temperatures during treatment and shorter processing times. The aims of this study were to analyze the characteristics of Napier grass-derived adsorbents related to the use of LPG for combustion pyrolysis process. The adsorbents were synthesized from Napier grass by chemical pretreatment using H_3PO_4, NaOH, and $Fe(NO3)_3$ before being fed to the furnace. Adsorbent characterization was carried out through the application of Brunauer–Emmett–Teller (BET) methods, scanning electron microscopy (SEM) with the energy-dispersive Xray spectroscopy (EDX) and X-ray diffraction (XRD). The percentage of burn off, removal efficiency of THMs, kinetic and isotherm adsorption on the Napier grass-derived adsorbent were examined. The THM species measured in this study were CF, BDCM, DBCM and BF. The current study was conducted at the Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University, Thailand in 2023.

MATERIALS AND METHODS

Raw materials and chemicals pretreatment

Napier grass was used as the main feedstock for the synthesis of the adsorbents. Napier plants were collected from a nearby farm in Chiang Mai, Thailand, and dried in order to reduce the moisture content. Prior to the pyrolysis process, harnessing solar energy to reduce moisture content to the lowest feasible level proves to be economically advantageous (FAO, 1985). Kers *et al.* (2010) and Onchieku *et al.* (2012) highlighted the importance of minimizing energy costs in the pyrolysis process. Napier grass has a different chemical composition compared to sugarcane and Swiss grass. This difference could affect the yield percentage obtained after combustion, particularly in relation to cellulose, hemicellulose, and lignin content. Napier grass exhibits a composition of 36.8%, 18%, and 23.4% (He *et al.,* 2017), respectively. The sugarcane comprises cellulose (39%) and lignin (23.09%), thus the combustion process might affect its composition and impact absorption efficiency. An analysis of the type and geographical distribution of Napier grass cultivation revealed that the cellulose, hemicellulose, and lignin content in Taiwan and Brazil showed no significant variations. Specifically, Taiwan reported values of 35.69%, 15.26%, and 18.03%, respectively (Vargas *et al.,* 2023). The air-dried Napier grass was chopped and blended to a size of 1–3 centimeter (cm), then dried in an oven at 60 °C for 48 hour (h). Subsequently, Napier grass pieces were pretreated for 2 h at 80°C in each solution that included 0.2 molar (M) H_3PO_4, 0.2M NaOH, and 0.05M $Fe(NO_3)$, (RCI-Labscan Company, Bangkok, Thailand). Then, it was dried in the oven for 48 h at 60°C. RESTEK (Pennsylvania, United States of America) supplied the standard solutions for THMs. The experiment used Milli-Q water (Ultra Analytic, ELGA, United Kingdom) to prepare all analytical solutions.

Synthesis of the adsorbents

Adsorbents derived from Napier grass were produced by activating dried Napier grass at 600 °C with LPG for a duration of 1 h. A temperature of 600 °C was selected because carbon is the predominant component found in Napier grass. When combustion occurs at a lower temperature (ranging from 200 to 400°C), there was a possibility that volatile substances may remain unburned, leading to potential blockage of the pore surface. Nevertheless, a combustion temperature of 600 °C is classified as a consistent burn. Carbon functions as an absorbent component, and when combusted at temperatures above 600 °C, the material structure may remain intact, leading to inefficient energy utilization (Boon *et al.,* 2017). The pilot furnace was supplied with around 1 kilogram (kg) of Napier grass. This study demonstrates the effective utilization of exhaust gases generated during the pyrolysis process for combustion purposes. The combination with LPG allows for burning to mitigate waste gas emissions from this process, which comprises 60 percent (%) CO_2, 39% carbonmonoxide (CO), and 1% other gases, as noted in earlier research (Sriboonnak, 2019). Pyrogas serves primarily as an energy source for the pyrolysis process. Implementing regulations for exhaust gas emissions is vital. The exact composition of waste is often indeterminate, leading to the inclusion of certain undesirable compounds in pyrogas. The method of incinerating substances to create charcoal can result in environmental pollution from the byproducts of combustion. For example, hydrogen sulfide can undergo oxidation, resulting in sulfur dioxide, a contributor to acid rain. Additionally, this gas is associated with the global warming effect. Consequently, it is crucial to control or modify the gas before it is emitted into the environment (Czajczyńska *et al.,* 2017). The process of pyrolysis results in the production of three main components: charcoal, tar, and gas, which are typically found in approximate proportions of 40%, 40%, and 20%, respectively (Bridgwater, 2012). Increasing the energy or value of the by-products produced is indeed achievable. Charcoal can effectively absorb harmful compounds, such as disinfection byproducts (DBPs), which are known to be carcinogenic. The gas may also be employed for activities following the recycling process, this study has recycled the produced waste gas. Furthermore, bio-oil has the potential to serve as a source of renewable energy (Mohammed *et al.,* 2015). Upon completion of one hour of heating, the adsorbents were cooled in an anaerobic environment. The required particle size (60–100 mesh) was then achieved by passing the adsorbents through a series of sieves. Following this, the adsorbents underwent rinsing with Milli-Q water to extract free ions, ensuring a pH range of 6 to 7, and were then placed in an oven at 60 °C for 48 hours to dry. The synthesized adsorbents were labeled as N-C. Additionally, materials that underwent pretreatment

with H_3PO_4, NaOH, and $Fe(NO_3)$ were synthesized at a temperature of 600 °C and are designated as N-A, N-Na, and N-Fe, respectively. Finally, the adsorbents obtained from Napier grass were employed for the adsorption of THMs. Subsequently, a comparison was made between the adsorption capacity of these adsorbents and that of activated carbon sourced from DC Fine Chemicals Limited in London, United Kingdom.

Characterization of the adsorbents

The surface area and pore size of the generated adsorbents were evaluated with the Autosorb-1-MP (Quanta Chrome, Anton Paar, Graz, Austria) through the nitrogen adsorption-desorption method at 77 Kelvin (K). The evaluation of the specific surface area was performed through the BET method (S_{BET}). The micropore size distribution of adsorbents was evaluated using the Barrett, Joyner, and Halenda (BJH) method. The materials' morphologies were evaluated using a field emission scanning electron microscope (FESEM, JSM-6335F, JEOL, Japan) equipped with an EDX detector (Inca, Oxford, United Kingdom), operating at 200 kilovolt (kV). The XRD patterns were utilized to characterize the synthesized adsorbents by assessing their crystalline structures. XRD analyses were conducted utilizing a Bruker/ D8ADVANCE diffractometer from Germany, with Cu Kα radiation and scanning XRD patterns within the range of Bragg's angle (2θ) = 10°–80°. The features of AC utilized in this investigation were guided by the findings of a previous study (Yimyam *et al.,* 2023). The points of zero charge (PZC) of the absorbents were identified using a batch equilibrium technique. The absorbent (0.1000 gram (g)) was placed in an Erlenmeyer flask and shaken with 100 millilter (mL) of deionized water at 200 rounds per minute (rpm) for 24 h, while the pH was adjusted from 1.0 to 13.0 using 0.1 M Hydrochloric acid (HCl) and 0.1 M NaOH. The initial pH ($pH_{initial}$) and the final pH (pH_{final}) after 24 h were measured and plotted to determine their relationship.

THM adsorption on the adsorbents

A solution of THMs (100 µg/L) was prepared by the dilution of the standard THMs solution using phosphate buffer (184 millimol (mM), pH 7.0). Following this, 100 mL of the THM solution was moved to a flask that included varying amounts of 0.050–0.300 g of the adsorbents. The adsorbent solutions were mixed at a rate of 200 rpm at ambient conditions (27-29 °C) for 6 hours, a time frame considered adequate to attain equilibrium as indicated by the adsorption kinetics studies (Sriboonnak, 2019). The samples were filtered using a 0.22-micrometer (µm) nylon filter. THMs were quantified applying an advanced methodology based on USEPA Method 551.1 (SEPA Method, 1995). The extraction of THMs was performed utilizing methyl tertiary butyl ether (MTBE), and the resulting upper MTBE layer will undergo concentration analysis through a gas chromatograph (GC) equipped with an electron capture detector (ECD) (Hewlett Packard, HP6890 GC, The United States of America). The VF-X fused silica capillary column, measuring 30 meter (m) in length and 0.32 millimeters (mm) in diameter with a film thickness of 0.1 µm, was employed for gas chromatography analysis, working with helium as the carrier gas. The calculation of the percentage removal (%removal) of THMs was performed using equation (Eqs.) 1 (Induvesa *et al.,* 2020):

$$\text{Removal}\ (\%) = \frac{(C_i - C_f)}{C_i} \times 100 \quad (1)$$

where C_i and C_f were the initial and final concentration (µg/L) of THMs, respectively.

The kinetics of THMs adsorption on the adsorbents were examined by altering the contact time from 0 to 24 h. The starting concentration of THMs was generally established at 100 µg/L in a 100 mL solution, accompanied by a dosage of 0.2000 g. The adsorption kinetic models consist of the pseudo-first order, pseudo-second order, and the intraparticle diffusion model. The models are used to analyze the data for the suitability and determine the adsorption capacity. The duration of contact is essential in the adsorption process. The analysis of kinetic data facilitates the identification of the rate constant, the order of steps in the adsorption process, and the specific step that controls the rate. The equations for the pseudo-first-order and pseudo-second-order models are presented in Eqs. 2 and 3, respectively (Induvesa *et al.,* 2020):

$$q_t = q_e \left(1 - e^{-k_1 t}\right) \quad (2)$$

$$q_t = \frac{q_e^2 k_2 t}{1+q_e k_2 t} \quad (3)$$

where q_t is the adsorption at a specific time (µg/g), q_e is the adsorption capacity when equilibrium is reached (mg/g), t is time (min), and k_1 (1/min) and k_2 (g/µg·min) are the rate constants for the pseudo-first order and pseudo-second order reactions, respectively. According to the pseudo-second-order equation, h is the initial adsorption rate **(**µg**/**g·min**)** at t = 0 and $t_{1/2}$ is half-life time can be estimated using Eqs. 4 and 5 (Induvesa *et al.,* 2020):

$$h = k_2 q_e^2 \quad (4)$$

$$t_{1/2} = \frac{1}{k_2 q_e} \quad (5)$$

The intra-particle diffusion model is expressed, using Eq. 6 (Induvesa *et al.,* 2020):

$$q_t = kt^{0.5} + c \quad (6)$$

In this context, k is the rate constant of the intra-particle diffusion model (µg/g·min$^{0.5}$) while C denotes the intercept constant associated with the thickness of the boundary layer (µg/g). To ascertain the adsorption isotherm, batch experiments were conducted with THM concentrations ranging from 50 to 1000 µg/L. A total of 0.2000 g of adsorbent was employed in a 100 mL solution. The adsorption isotherm experiments were gathered from four models: the Linear, Langmuir, Freundlich, and Dubinin and Radushkevich (D-R) isotherms to evaluate the adsorption behavior of THM on the adsorbents. The Linear isotherm model was represented by Eqs**.** 7 (Induvesa *et al.,* 2020):

$$q_e = k_p C_e \quad (7)$$

The variable *qe* represents the adsorption capacity (µg/g) at equilibrium, while k_p denotes the linear constant, and C_e indicates the equilibrium concentration (µg/l).

The Langmuir isotherm model is expressed using Eq. 8 (Induvesa *et al.,* 2020):

$$q_e = \frac{q_m K_L C_e}{1+K_L C_e} \quad (8)$$

Where, K_L is the Freundlich constant (µg/g)

The Freundlich model is expressed using Eq. 9 (Induvesa *et al.,* 2020):

$$q_e = K_f C_e^{1/n} \quad (9)$$

Where, K_f is the Freundlich constant (µg/g), and *1/n* is the adsorption intensity (dimensionless).

The D**-**R isotherm equation is expressed, using Eqs 10 to 12 (Prarat *et al.,* 2018):

$$q_e = q_{DR} \exp^{-(\beta\varepsilon^2)} \quad (10)$$

$$\varepsilon = RT \ln\left(1+\frac{1}{C_e}\right) \quad (11)$$

$$E = \frac{1}{\sqrt{2\beta}} \quad (12)$$

Here, ε represents the Polanyi potential, β denotes the Dubinin-Radushkevich constant (mol^2/J^2), q_{DR} indicates the theoretical isotherm saturation capacity (µg/g), and E means the mean free adsorption energy as kilojules per mole (KJ/mol). Duplicate analyses were performed on all samples.

RESULTS AND DISCUSSION

Pore distribution of the adsorbent

Fig. 1 illustrates the N_2 adsorption-desorption isotherms for N-C, N-Fe, N-Na, and N-A. The international union of pure and applied chemistry (IUPAC) classification (Siyasukh *et al.,* 2018) shows that the N_2 adsorption-desorption isotherm of the four adsorbents displays Type-I and Type-IV shapes (Table 1). The H3-hysteresis loop indicates the existence of micropores and slit-shaped mesopores within the macropore walls (Sing, 1982). Other studies (Yimyam *et al.,* 2023; Muniandy *et al.,* 2014) also reported similar findings, identifying Type-I and Type-IV shapes for AC derived from rice husk treated

with NaOH and from fabric treated with $Fe(NO_3)$. The cumulative micropore size distribution for the four materials analyzed in this study is depicted in Fig. 2. The cumulative particle size distribution curves illustrate different patterns for each material analyzed, indicating that the N-C material exhibits the greatest degree of size, succeeded by N-Na, N-A, and N-Fe. Findings related to pore distribution suggest that absorbents sourced from Napier grass display a range of small and varied pore sizes. The study reveals that the application of LPG and chemicals during the pretreatment of Napier grass-derived adsorbent results in the creation of micropores and mesopores. Table 1 showns the physical properties of the Napier grass-derived adsorbents.

The % burn-off for N-C, N-Fe, N-A, and N-Na were recorded at 73.3%, 57.1%, 56.2%, and 58.3%, respectively. The % burn-off analysis shows that applying chemical pretreatment to the adsorbent enhances the carbon yield percentage (% yield C), surpassing non-pretreated materials. N-A obtained a highest C yield of 43.8% due to the inclusion of H_3PO_4 during the pretreatment. This acid boosts the breakdown of materials, assists in water removal, and fosters the restructuring of the biopolymers that form the AC. This process facilitates the transformation of aliphatic compounds into aromatic ones, leading to an increased yield of adsorbent (Shi *et al.,* 2019; Teng *et al.,* 1998). The S_{BET} of N-C, N-Fe, N-A, and N-Na were measured at 182.5, 148.2, 142.3, and 115.1 m^2/g, respectively. Prior to the production of absorbents, the chemical pretreatment may contribute to a reduction in the carbon content of the feedstock structure. Tsai *et al.* (2018) found that the application of an alkaline solution to dried Napier grass resulted in a reduction of hemicellulose and lignin content by 61.1% and 63.0%, respectively. Findings from Yeh *et al*. (2016) revealed that hemicellulose and lignin experienced a reduction of 77.0%. Subsequent to the use of the dilute acid, the hemicellulose content

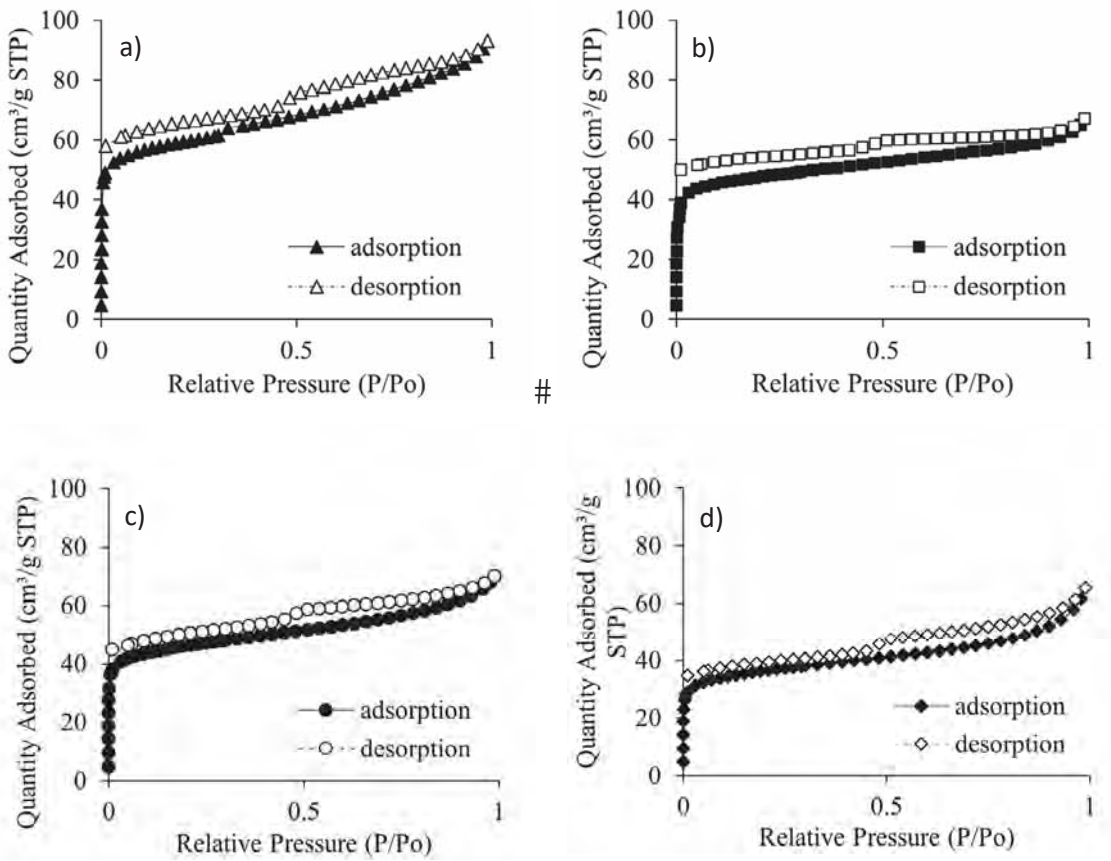


Fig. 1: N_2 adsorption and desorption isotherms of Napier grass-derived adsorbents a) N-C, b) N-Fe, c) N-A, and d) N-Na

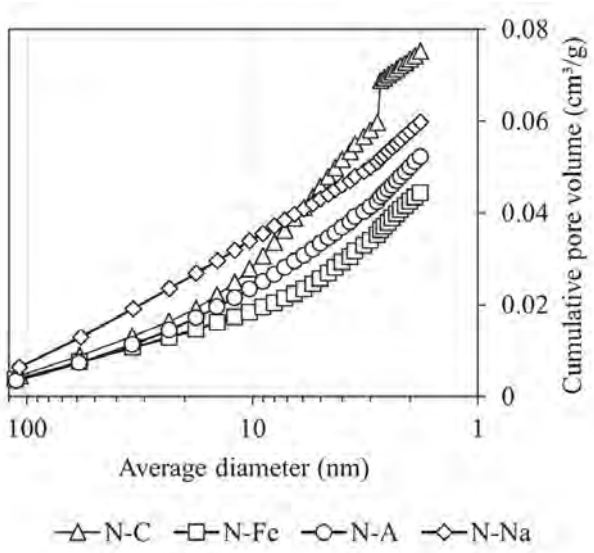


Fig. 2: The pore volume distribution of Napier grass-derived adsorbents

Table 1: Physical properties of the Napier grass-derived adsorbents

Samples	Type of isotherm	% Burn-off (%)	S_{BET} (m^2/g)	S_{mic} (m^2/g)	S_{mic}/S_{BET} (%)	V_{tot} (cm^3/g)	V_{mic} (cm^3/g)	V_{mic}/V_{tot} (%)	D_p (nm)
N-C	I, IV	73.3	182.5	123.5	67.78	0.1382	0.06580	47.61	4.930
N-Fe	I, IV	57.1	148.2	103.4	69.77	0.09859	0.05401	54.78	4.672
N-A	I, IV	56.2	142.3	92.35	64.90	0.1032	0.04927	47.74	4.569
N-Na	I, IV	58.3	115.1	69.09	60.02	0.0924	0.03612	39.09	6.026

in the material decreased to 81.1% of the dried raw material. The specific surface area of the chemically pretreated adsorbent showed no significant difference compared to the N-C. Conversely, the N-Na of the micropore surface (S_{mic}) was 1.7 times lower than the N-C. The study examined an adsorbent whose mean pore diameter (D_p) exceeded 2 nanometer (nm) (mesopore), indicating a greater prevalence. The D_p depends within the range of 4.569 to 6.026 nm. The total pore volume (V_{tot}) and microporous volume (V_{mic}) (Table 1), exhibited no significant differences among the four adsorbents. The total volume of chemically adsorbents showed minimal change, decreasing from 0.1382 to 0.09240 cubic centimeter per gram (cm^3/g). The V_{mic} values were recorded as 0.06580, 0.05401, 0.04927, and 0.03612 for N-C, N-Fe, N-A, and N-Na, respectively. An important observation was identified regarding the pore structure of the adsorbent produced through chemical pretreatment involving N-A, N-Fe, and N-Na. The characteristics of the pore structure in this case drop when compared to the carbon that has not undergone pretreatment. The phenomena observed may be linked to the constriction of carbon structures, leading to a decrease in porosity formation.

Surface morphology of the adsorbent

The SEM images of N-C (Fig. 3a), N-Fe (Fig. 3b), N-A (Fig. 3c), and N-Na (Fig. 3d) at zoom of 500x and 10,000x. The microscopy images of all Napier grass-derived adsorbents displayed an irregular shape (at 500x, 50 µm) and a slightly rough surface texture (at 10,000x, 1 µm). The disruption of the biomass structure, resulting from the degradation of different volatile substances during chemical pretreatment with LPG, could explain this phenomenon. Similarly, charcoal produced from Napier grass and banana trunk treated with H_3PO_4 developed pores on its rough surface after being pyrolyzed at 450–850 °C (Danish *et al.,* 2018; Siyasukh *et al.,* 2018; Adesemuyi *et al.,* 2020; Yimyam *et al.,* 2023). The formation of pores and cavities occurs due to the evaporation

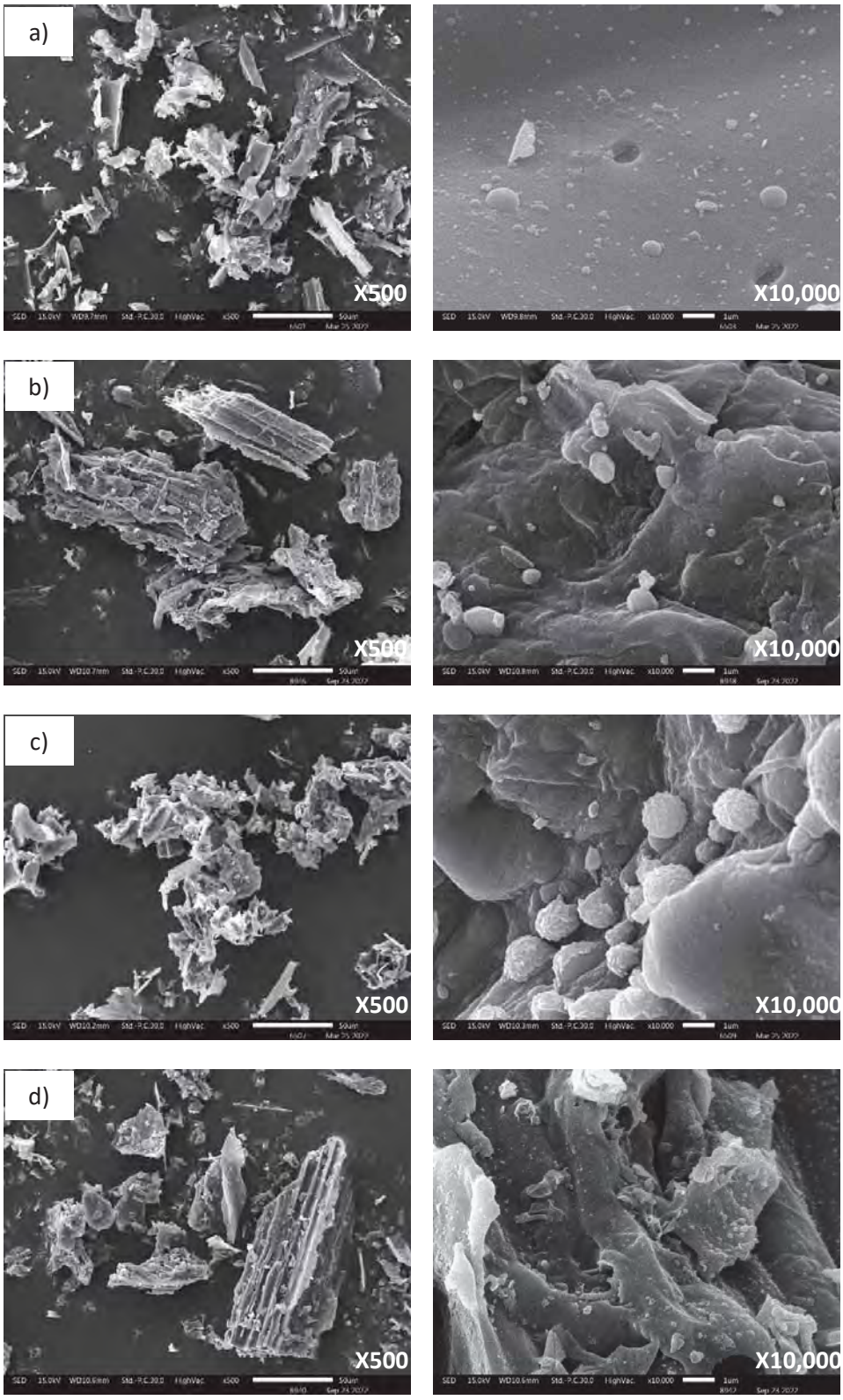


Fig. 3: SEM micrographs of Napier grass-derived adsorbents: a) N-C, b) N-Fe, c) N-A, and d) N-Na

and gasification of the activating chemicals, including NaOH, H_3PO_4, and $Fe(NO_3)$, during the pretreatment process. Consequently, the area that was once occupied during the impregnation phase is restored. The small particles included $Fe(NO_3)$, H_3PO_4, and NaOH, which were added into the raw material during the synthesis process. It could be demonstrated that including them results in the decomposition into adsorbent derived from Napier grass. The elemental composition of adsorbents sourced from Napier grass is detailed in Table 2. The EDX measurements of the adsorbents revealed three main elements: carbon (C), oxygen (O), and potassium (K). As outlined in Table 2, the additional elements identified consist of silicon (Si), chlorine (Cl), and calcium (Ca). A notable decrease in carbon content occurred after the chemical pretreatment, which led to an increase in the percentage of oxygen content. This phenomenon might be related to the evaporation of volatile compounds (Tsai *et al.,* 2018). This research revealed that the concentrations of atomic iron (Fe), phosphorus (S), and sodium (Na) in the N-Fe, N-A, and N-Na adsorbents were measured at 4.69%, 15.41%, and 2.56%, respectively. The identification of Fe, P, and Na elements within these adsorbents implies that these elements might interact with the adsorbent surfaces throughout the chemical pretreatment phase.

Crystal textura

Fig. 4 presents the XRD patterns of the synthesized adsorbents. The intensity of the diffraction patterns was defined in relation to Bragg's angle (2θ). The prominent peaks were observed at a 2θ value ranging from approximately 20° to 42°, suggesting the presence of elements showing an amorphous structure. Adsorbents sourced from Napier grass were predominantly amorphous, while also showing some degree of crystalline structure (Simões *et al.,* 2024). Consistent with the composition analysis conducted

Table 2: Elemental analysis of the synthesized adsorbents

Sample	Atomic (%)								
	C	O	K	Fe	Si	P	Na	Cl	Ca
N-C	87.38	11.29	1.33	N/D	N/D	N/D	N/D	N/D	N/D
N-Fe	69.15	17.27	4.69	7.32	1.56	N/D	N/D	N/D	N/D
N-A	39.38	38.12	0.64	N/D	6.45	15.41	N/D	N/D	N/D
N-Na	79.01	14.90	1.39	N/D	1.18	N/D	2.56	0.49	0.47

N/D= not detected

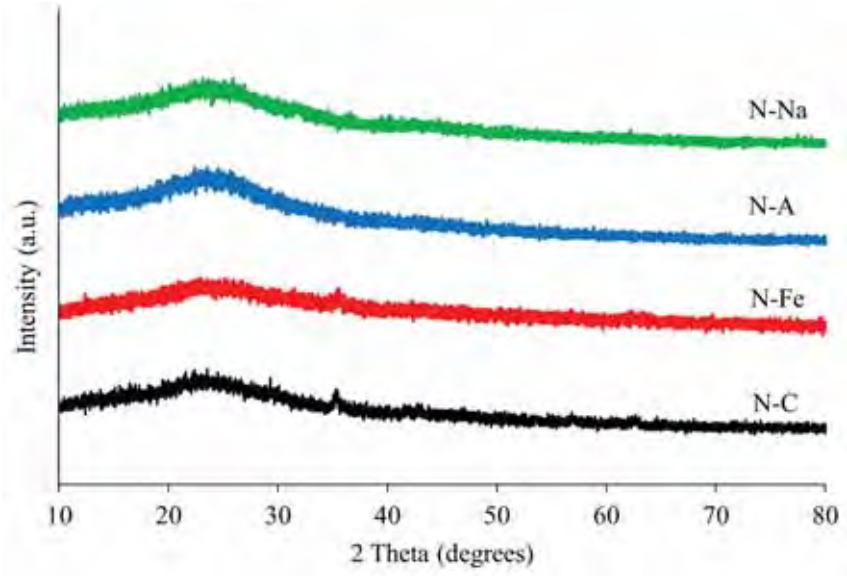


Fig. 4: XRD patterns of all the adsorbents

by Shaaban *et al.* (2013), it was determined that the amorphous biomass was modified by the presence of hemicellulose and lignin. The detection of broad peaks at 26° and 42° serves as evidence for the presence of porous and amorphous structures in the adsorbent. This specific characteristic is beneficial for its use in adsorption applications (Tongpoothorn *et al.,* 2010). Additionally, the compounds of Fe, Na, and S were identified at 2θ values of 35°, 32°, and 28°, respectively. The outcomes correspond with the elemental analysis, implying that the elements originate at the adsorbent's surface.

Point of charge of absorbent

The point of zero charge for the four adsorbents is displayed in Fig. 5. The pH of PZC values for N-C, N-Fe, N-A, and N-Na were determined as 8.0, 7.5, 8.5, and 10.0, respectively. The pH of the water solution equates to the PZC value of each adsorbent, indicating that the surfaces of the adsorbents exhibited a neutral or nearly zero charge (Nath *et al.,* 2021). Furthermore, protonation reaction on the adsorbent surface occur when the solution's pH is below the PZC value, which causes the surface to acquire a positive charge. The pH of the aqueous solution corresponds to the PZC value of each adsorbent, resulting in surfaces exhibiting a neutral or almost zero charge. Conversely, deprotonation reactions are initiated when the adsorbent surface becomes negative, which occurs when the solution's pH exceeds the PZC value (Pinky, 2023). Throughout this study, all adsorbent materials were employed to capture the THMs. The solution's pH was modified to 7.0 through the addition of phosphate buffer. Consequently, the surfaces of the N-C, N-Fe, and N-A adsorbents may exhibit a positive charge relative to neutral charge, given that the pH of the THMs is below the PZC value. This could also signify a surface that is positively charged in comparison to N-Na.

Effects of the adsorbent dosage

The impact of different adsorbent doses on the removal efficiency of THMs, utilizing an adsorbent made from Napier grass, is depicted in Fig. 6. As the dosage rises from 0.5000 to 3.0000 grams per liter (g/L), the percentage of THMs removed also shows a corresponding increase. The highest removal efficiency of THMs was achieved at 94.43% with N-A provided at a dosage of 3.0 g/L. Previous research investigated the influence of water pH on the generation of trihalomethanes (THMs). The presence of THMs has been linked to water with a pH of 8 or higher. For optimal utilization of this adsorbent, it is important to consider the pH of bodily fluids, since it may impact the absorption capabilities (Hung *et al.,* 2017; Sriboonnak *et al.,* 2021). Furthermore, Napier

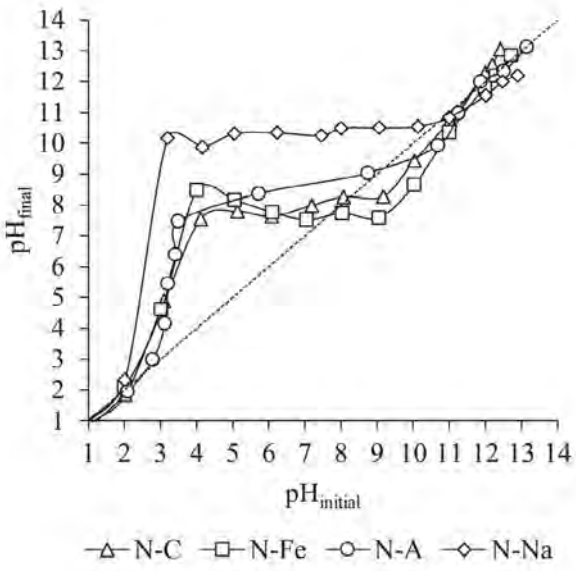


Fig. 5: PZC of the Napier grass-derived adsorbent

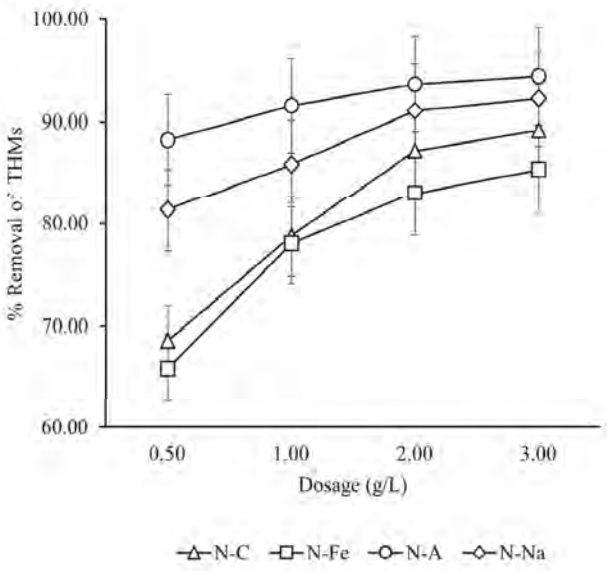


Fig. 6: The removal of THMs by Napier grass-derived adsorbents

grass biomass is known to generate an adsorbent that features a hydrophobic surface (Mohammed *et al.,* 2015). This leads to a more efficient application of THMs to the pores of the adsorbent. Therefore, at an increased adsorbent dosage (>2.0000 g/L), there will be an abundance of adsorption sites available for the adsorbed reaction. Moreover, an elevated dosage could lead to the accumulation of adsorbents, which would reduce the overall surface area and consequently lower the adsorption capacity (Malik *et al.,* 2018; Semerjian, 2010). In this study, an adsorbent dosage of 2.0000 g/L was utilized for the kinetic and isotherm adsorption studies.

Kinetic and isotherm adsorption

Fig. 7 displays the curves illustrating the pseudo-second order kinetic dependence for THMs capacities, which correspond to the N-C, N-Fe, N-A, N-Na, and AC

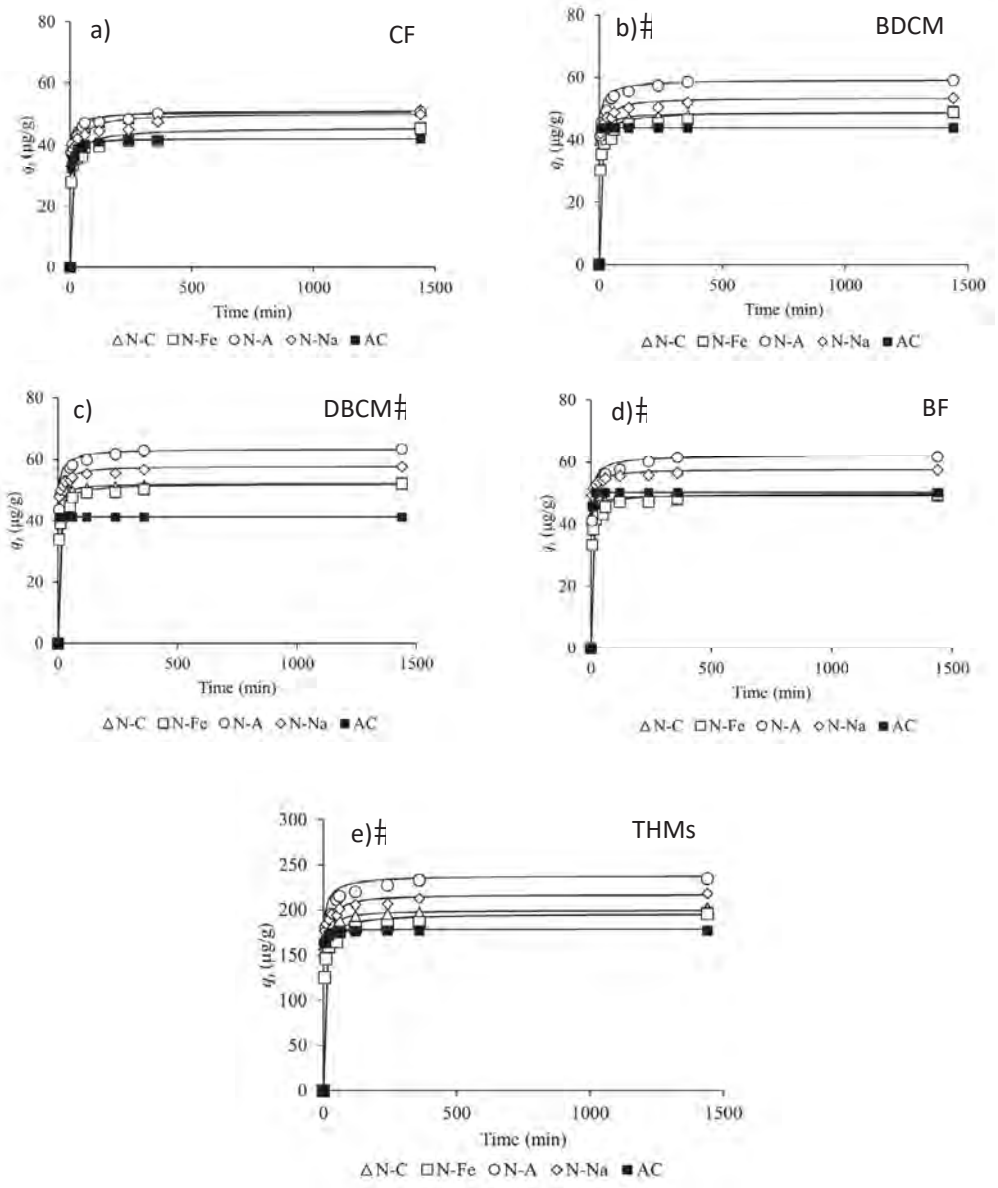


Fig. 7: Adsorption kinetics of CF, BDCM, DBCM, BF, and THMs on N-C, N-Fe, N-A, N-Na, and AC adsorbents (a-e), with a solid/liquid ratio of 2 g/L; solid lines represent results from the pseudo-second order model

adsorbents, respectively. The data were obtained using an adsorbent dose of 2.0000 g/L and a THMs concentration of 100 µg/L. Initially, THMs were absorbed at a high rate, but this process leveled off after approximately 120 minutes. As a result, the absorption rate became independent of time. N-A showed the greatest removal capacity, despite possessing a lower surface area of 142.3 m²/g compared to AC (740.5 m²/g) (Yimyam *et al.*, 2023). The analysis of pore sizes within carbon indicated that N-A exhibited larger pores measuring 2 nm, highlighting the presence of mesopores in addition to micropores (type I), that were measured at 4.569 nm. In contrast, AC displayed smaller pores with a measurement of

Table 3: Parameters of the pseudo-first order and pseudo-second order kinetic models for the removal of THMs, CF, BDCM, DBCM, and BF

Samples and THMs	$q_{t,exp}$ (µg/g)	Pseudo-first order			Pseudo-second order				
		k_1/min	q_t (µg/g)	R^2	k_2 (g/µg/min)	q_t (µg/g)	h (µg/g/ min)	$t_{1/2}$ (min)	R^2
N-C									
THMs	192.7	0.0053	189.7	0.888	0.0045	194.4	170.0	2.0	0.996
CF	47.6	0.0046	46.2	0.771	0.010	48.7	23.9	1.2	0.992
BDCM	46.7	0.0074	46.2	0.838	0.019	47.0	41.8	1.1	0.994
DBCM	50.5	0.0076	49.9	0.798	0.023	50.7	58.7	0.9	0.997
BF	47.9	0.013	48.1	0.884	0.030	48.1	68.4	0.7	0.998
N-Fe									
THMs	180.9	0.0046	172.4	0.759	0.0020	184.8	68.2	2.7	0.989
CF	39.6	0.0034	38.2	0.738	0.0087	41.4	15.0	2.8	0.979
BDCM	45.1	0.0048	42.6	0.780	0.0072	45.9	15.1	3.0	0.986
DBCM	49.0	0.0052	46.7	0.755	0.0074	49.8	18.4	2.7	0.992
BF	47.2	0.0055	45.1	0.753	0.0088	47.7	20.0	2.4	0.994
N-A									
THMs	220.2	0.0094	184.6	0.950	0.0018	225.0	92.9	2.4	0.982
CF	47.4	0.0069	42.5	0.726	0.011	48.2	25.2	2.8	0.976
BDCM	55.6	0.0092	44.5	0.879	0.0074	56.6	23.6	2.5	0.980
DBCM	59.7	0.010	47.8	0.887	0.0065	60.9	24.2	2.4	0.984
BF	57.5	0.0097	44.6	0.906	0.0060	59.4	21.3	1.9	0.985
N-Na									
THMs	205.5	0.0048	178.8	0.880	0.0045	206.9	193.4	1.1	0.990
CF	44.6	0.0039	38.8	0.894	0.015	45.3	31.4	1.4	0.967
BDCM	50.2	0.0051	44.4	0.877	0.016	50.5	40.2	1.2	0.988
DBCM	55.2	0.0052	48.6	0.866	0.019	55.5	57.4	0.96	0.995
BF	55.4	0.0060	47.0	0.740	0.024	55.8	73.6	0.76	0.997
AC									
THMs	174.1	0.022	2.74	0.845	0.0095	178.6	303.3	0.59	0.999
CF	38.8	0.019	2.43	0.888	0.0098	42.2	17.5	2.4	0.998
BDCM	43.87	N/D	N/D	N/D	1.04	43.8	2000.0	0.022	0.999
DBCM	41.25	N/D	N/D	N/D	0.98	41.3	1666.6	0.025	0.999
BF	50.15	N/D	N/D	N/D	0.12	50.2	303.0	0.16	0.999

N/D= not detected

3.442 nm (Yimyam *et al.,* 2023). Furthermore, Qin (2022) reported the ability of the Napier grass adsorbent to absorb the heavy metals zinc and cadmium. The efficiency of THM adsorption on N-A is significantly higher than that observed with AC. The removal of each THM molecule using AC was achieved within 60 minutes, leading to the establishment of adsorption equilibrium. Compared to other substances, the N-A exhibited improved adsorption efficiency for THMs, which can be attributed to its increased carbon yield (Teng *et al.,* 1998). The results demonstrate that the adsorption process reached an equilibrium state in a relatively short time. Fig. 7 illustrates the adsorption capacity of four THMs on the adsorbent (Fig. 7). The results demonstrated that the time needed to reach equilibrium for all four types of Napier grass adsorbents was 120 minutes, with the exception of the substances adsorbed CF using AC. Achieving equilibrium takes more than approximately 90 minutes. The adsorption efficiency, indicated as qt, for each THM was analyzed using time-dependent plots. The order in terms of adsorption efficiency in all absorbents was DBCM > BF > BDCM > CF, with the exception of BF adsorbed by AC. These findings demonstrate that the adsorbent underwent a chemical pre-treatment, leading to improved chemical absorption capabilities in comparison to AC. Additionally, the adsorption kinetic parameters are presented in Table 3. The study applied pseudo-first-order and pseudo-second-order models to analyze the results, reporting correlation coefficients (R^2) for all adsorption kinetic studies. Regarding to the pseudo-first order model, the adsorption kinetic data

Table 4: Parameters of the intraparticle diffusion kinetic models for the removal of THMs, CF, BDCM, DBCM, and BF

Samples and THMs	q_{exp} (µg/g)	Intra-particle diffusion model					
		k_1 (g/µg/min$^{0.5}$)	c_1 (µg/g)	R^2	k_2 (g/µg /min$^{0.5}$)	c_2 (µg/g)	R^2
			N-C				
THMs	192.7	4.34	157.03	0.895	0.29	190.32	0.962
CF	47.6	0.61	34.47	0.779	0.13	46.45	0.984
BDCM	46.7	1.04	38.00	0.953	0.070	46.24	0.935
DBCM	50.5	0.95	42.72	0.947	0.052	50.01	0.937
BF	47.9	0.74	41.84	0.938	0.044	47.58	0.928
			N-Fe				
THMs	180.9	7.66	117.33	0.853	0.55	175.03	0.994
CF	39.6	1.64	26.50	0.814	0.20	37.74	0.974
BDCM	45.1	2.00	28.05	0.858	0.14	43.48	0.971
DBCM	49.0	2.14	31.32	0.865	0.11	47.73	0.967
BF	47.2	1.89	31.47	0.849	0.093	46.08	0.956
			N-A				
THMs	220.2	8.92	147.01	0.977	0.44	219.61	0.636
CF	47.4	1.68	33.70	0.914	0.11	46.87	0.681
BDCM	55.6	2.21	37.12	0.967	0.11	55.38	0.664
DBCM	59.7	2.50	39.13	0.970	0.10	59.70	0.619
BF	57.5	2.52	37.06	0.956	0.12	57.65	0.561
			N-Na				
THMs	205.5	3.83	170.93	0.897	0.47	200.90	0.898
CF	44.6	0.84	36.07	0.690	0.20	42.64	0.897
BDCM	50.2	1.08	40.38	0.922	0.12	49.03	0.886
DBCM	55.2	1.04	46.29	0.929	0.086	54.40	0.888
BF	55.4	0.88	48.18	0.913	0.069	54.83	0.928
			AC				
THMs	174.1	3.56	155.09	0.989	0.073	175.20	0.565
CF	38.8	1.32	30.48	0.922	0.031	41.04	0.695
BDCM	43.87	N/D	N/D	N/D	N/D	N/D	N/D
DBCM	41.25	N/D	N/D	N/D	N/D	N/D	N/D
BF	50.15	N/D	N/D	N/D	N/D	N/D	N/D

N/D= not detected

indicate that at equilibrium in the kinetic adsorption test, the pseudo second-order kinetic exhibited a higher level of efficiency in the adsorption of THMs for all types of adsorbents. The adsorption of THMs on the adsorbent sourced from Napier grass is best described by the pseudo-second-order kinetic model, indicating that the process is likely influenced by chemisorption mechanisms. The initial adsorption rates (*h*) of N-Na on the observed to be 1 to 2 times more rapid than those of N-A and N-Fe. This enhancement in adsorption

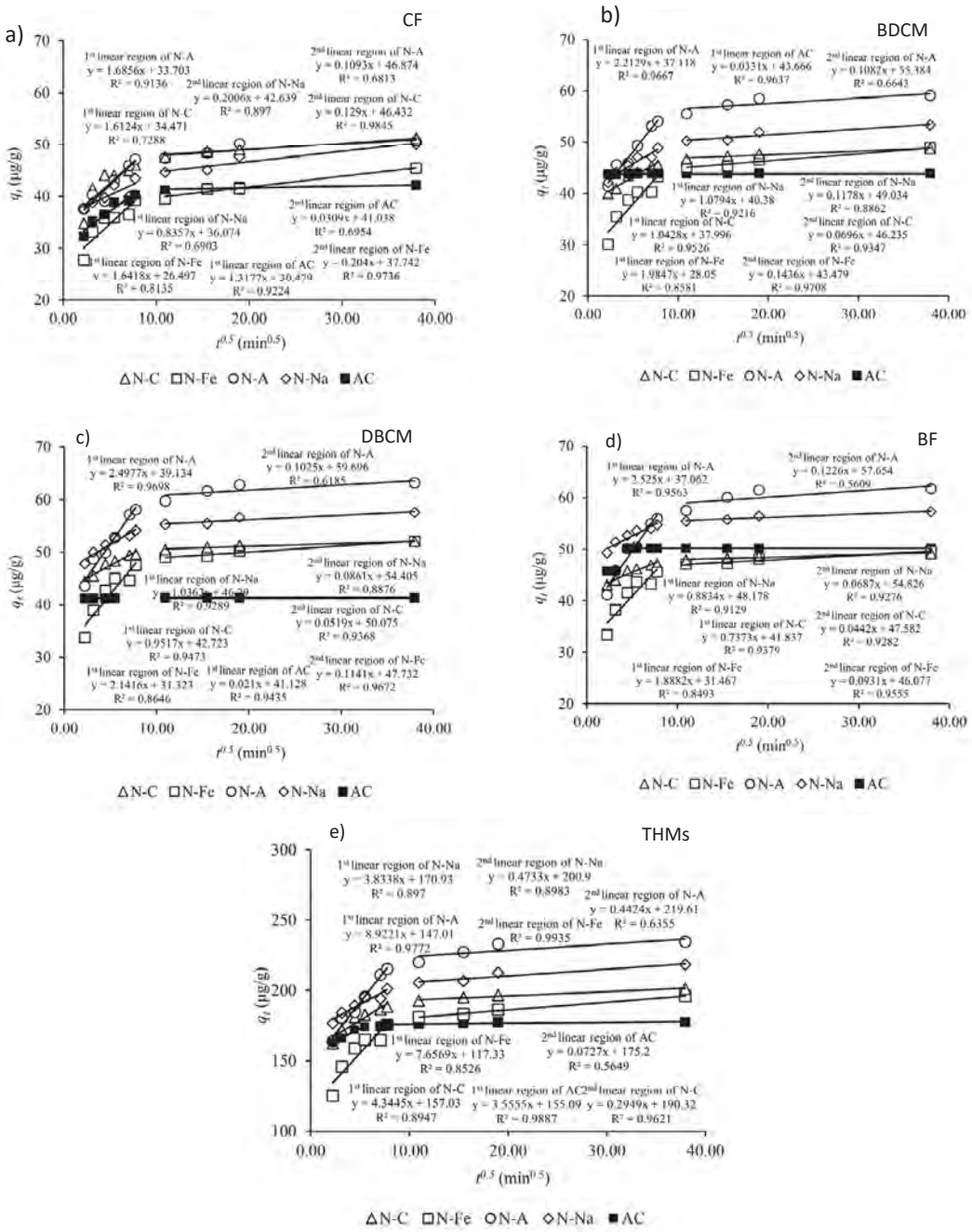


Fig. 8: Adsorption kinetics of CF, BDCM, DBCM, BF and THMs on N-C, N-Fe, N-A, N-Na and AC
(Adsorbents (a-e) with a solid/liquid ratio of 2 g/L; solid lines represent results from the intraparticle diffusion model)

Table 5: Isotherm parameters of THMs by Linear, Langmuir, Freundlich and Dubinin and Radushkevich equations

Samples and THMs	Linear		Langmuir			Freundlich			Dubinin and Radushkevich			
	k_1 (L/μg)	R^2	q_m (μg/g)	K_L (L/μg)	R^2	K_f (μg/g)	1/n	R^2	q_{DR} (μg/g)	B (mol^2/KJ^2)	E (KJ/mol)	R^2
						N-C						
THMs	3.81	0.950	6248.35	$9.2x10^{-4}$	0.987	12.47	0.81	0.973	2399.80	$4.52x10^{-3}$	$1.50x10^{-2}$	0.974
CF	2.32	0.936	1372.63	$2.77x10^{-3}$	0.984	7.71	0.78	0.966	600.32	$6.99x10^{-4}$	$2.67x10^{-2}$	0.981
BDCM	3.44	0.933	1433.86	$3.90x10^{-3}$	0.983	10.38	0.78	0.964	619.10	$3.49x10^{-4}$	$3.78x10^{-2}$	0.974
DBCM	5.34	0.940	1234.84	$6.57x10^{-3}$	0.988	14.94	0.77	0.970	577.58	$1.33x10^{-4}$	$6.13 x10^{-2}$	0.967
BF	7.55	0.984	65569.60	$1.20x10^{-4}$	0.984	6.40	1.04	0.981	627.01	$1.12x10^{-4}$	$6.69x10^{-2}$	0.976
						N-Fe						
THMs	2.74	0.970	5620.85	$7.6x10^{-4}$	0.998	4.27	0.85	0.985	2322.11	$9.89x10^{-3}$	$7.11x10^{-3}$	0.965
CF	1.88	0.974	2168.29	$1.12x10^{-3}$	0.989	3.61	0.88	0.980	594.87	$1.46 x10^{-3}$	$1.85x10^{-2}$	0.971
BDCM	2.56	0.961	1320.55	$3.20x10^{-3}$	0.994	7.17	0.80	0.977	592.45	$6.71x10^{-4}$	$2.73x10^{-2}$	0.966
DBCM	3.50	0.968	1379.29	$3.90x10^{-3}$	0.995	9.85	0.79	0.984	552.84	$3.23x10^{-4}$	$3.94x10^{-2}$	0.961
BF	4.22	0.994	4923.72	$9.45x10^{-4}$	0.994	5.11	0.96	0.991	585.73	$3.01x10^{-4}$	$4.07 x10^{-2}$	0.966
						N-A						
THMs	4.36	0.950	14353.83	$3.4x10^{-4}$	0.957	7.16	1.00	0.950	1781.05	$2.14x10^{-3}$	$1.53x10^{-2}$	0.941
CF	2.89	0.949	5492.68	$5.41x10^{-4}$	0.952	2.24	1.05	0.946	443.11	$3.13x10^{-4}$	$4.00x10^{-2}$	0.931
BDCM	4.01	0.950	4752.16	$9.05x10^{-4}$	0.954	4.01	1.00	0.950	467.08	$1.73x10^{-4}$	$5.38 x10^{-2}$	0.935
DBCM	5.93	0.939	2594.17	$2.67x10^{-3}$	0.948	7.94	0.93	0.943	432.14	$6.80x10^{-5}$	$8.60x10^{-2}$	0.920
BF	6.89	0.967	29558.44	$2.35x10^{-4}$	0.967	4.30	1.13	0.960	460.03	$7.40x10^{-5}$	$8.22x10^{-2}$	0.968
						N-Na						
THMs	2.11	0.958	4693.80	$6.4x10^{-4}$	0.982	6.14	0.83	0.973	1613.16	$6.81x10^{-3}$	$8.57x10^{-3}$	0.947
CF	1.22	0.969	1404.44	$1.13x10^{-3}$	0.986	2.31	0.88	0.979	378.26	$1.12x10^{-3}$	$2.11x10^{-2}$	0.963
BDCM	1.78	0.956	1064.89	$2.51x10^{-3}$	0.983	4.78	0.81	0.973	411.19	$5.92x10^{-4}$	$2.91x10^{-2}$	0.948
DBCM	2.91	0.946	924.48	$5.14x10^{-3}$	0.980	8.76	0.77	0.969	404.93	$2.19x10^{-4}$	$4.78x10^{-2}$	0.930
BF	4.54	0.956	3469.70	$1.40x10^{-3}$	0.962	5.38	0.96	0.958	428.51	$1.33x10^{-4}$	$6.14x10^{-2}$	0.937
						AC						
THMs	11.96	0.874	76475.43	$1.6x10^{-4}$	0.873	0.00	5.45	0.998	13811.87	$1.75x10^{-3}$	16.89	0.993
CF	5.71	0.739	13835.44	$4.1x10^{-4}$	0.737	0.00	4.17	0.924	4703.14	$5.64x10^{-4}$	29.78	0.943
BDCM	13.30	0.719	24008.57	$5.6x10^{-4}$	0.719	0.00	0.16	0.778	411.19	$5.92x10^{-4}$	29.06	0.952
DBCM	23.14	0.832	36118.43	$6.4x10^{-4}$	0.832	0.00	7.46	0.882	404.93	$2.19x10^{-4}$	47.75	0.917
BF	18.81	0.817	25638.10	$7.4x10^{-4}$	0.871	0.39	2.62	0.831	945.58	$2.90x10^{-5}$	132.08	0.864

may be attributed to the larger mesopore diameters, which likely facilitated a more efficient internal pore diffusion rate. The D_p values were measured as follows: 6.026 nm for N-Na, 4.930 nm for N-C, 4.672 nm for N-Fe, and 4.569 nm for N-A (Table 1). When considering the $t_{1/2}$, the order of $t_{1/2}$ on THMs, from highest to lowest, was determined to be N-Fe, followed by N-A, N-C, N-Na, and finally AC. The effect of half-life remains unaffected by the initial adsorption rates. Among all adsorbents, BF has the greatest adsorption capacity and the most rapid kinetics, except for AC, which showed fast adsorption for BDCM, suggesting a strong correlation with the dipole moment. Typically, the process of adsorption in the aqueous phase is comprised of three mass transfer steps. The adsorbate undergoes transport through a layer of adsorbent particulates in the initial stage, known as film or external diffusion. The subsequent stage is known as intraparticle or pore diffusion. The final phase involves the adsorption of the adsorbate onto the active sites located on the adsorbent surface (Wang *et al.,* 2023; Liu *et al.,* 2009). This study applied an intraparticle diffusion model to examine the diffusion process affecting the adsorption of THM onto N-C, N-Fe, N-A, and N-Na, in relation to AC. Fig. 8 presents the plots of q_t versus $t_{1/2}$ for four THMs that have been adsorbed onto their respective adsorbents. As depicted in Fig. 8, the intraparticle diffusion curves reveal two linear segments concerning the adsorption of THMs, including CF, BDCM, DBCM, and BF onto the adsorbents. Most graphs exhibit an initial slope indicative of border diffusion effects, followed by a second slope that reflects pore diffusion effects. The graphs demonstrate that a uniform linear relationship exists among the BDCM, DBCM, and BF compounds, corroborating the conclusions drawn from AC. Table 4 was presented the parameters determined for the intraparticle diffusion model. The measured pore diffusion rate constant (k_{p2}) exhibited a lower value than the boundary diffusion rate constant (k_{p1}), suggesting that the adsorption process of the smallest four THMs is controlled by the pore diffusion step. The study aimed to determine the influence of the initial THM concentration on removal efficiency, with the adsorbent quantity held steady at 2.0000 g/L and the THM concentration adjusted over a defined equilibrium duration of 6 hours. Four different adsorption isotherm models—linear, Langmuir, Freundlich, and Dubinin and Radushkevich—have been used to examine the data. The findings indicated that N-C exhibited a greater removal capacity compared to AC and the chemical pretreatment adsorbents (N-A, N-Fe, and N-Fe). The adsorption capacity (as known as q_e) of THM species was measured on N-C, yielding the following results: CF (585.84 µg/g), BDCM (605.88 µg/g), DBCM (566.72 µg/g), and BF (569.76 µg/g). The indication of the absorbents varied based on the molecular structure of the THM species. The results concerning the adsorption of four types of THM derivatives on charcoal derived from Napier grass indicate a trend of increased adsorption that is associated with the molecular weight of the compounds in each adsorbent. BF demonstrated the greatest absorption, followed by BDCM, then DBCM, and finally CF. Activated carbon adsorption exhibited a pattern similar to the kinetic effect; THM derivatives are adsorbed onto the surface, demonstrating the isotherm effect. This observed phenomenon can be linked to the characteristics of the pore structure and the interactions occurring between the adsorbate and the adsorbent (Srivastava *et al.,* 2021). The isotherm parameters derived for the four models concerning N-C, N-Fe, N-A, N-Na, and AC are presented in Table 5. The identification of a suitable model was achieved through the examination of R^2. Furthermore, the adsorption data of THMs on the adsorbents mostly correspond to the Langmuir isotherm model, except for AC, which correlates more closely with the Freundlich model. This implies that the THMs that adhered to the adsorbents sourced from Napier grass established a monolayer, in contrast to activated carbon, which resulted in multilayer formation. The adsorption intensity (*1/n*) of approximately 1 was determined for the adsorption of all THMs on four adsorbents (N-C, N-A, N-Na, and N-Fe) using the Freundlich model. The investigations were made in the order of AC > N-C > N-A > N-Na > N-Fe. The free adsorption energy (*E*) was used to determine the character of the adsorption process using the D-R isotherm model. The *E* values of THMs deposited on adsorbents ranged from 0.00857 to 132.08 kilojoules per mole (kJ/mol), with most values getting below 4 kJ/mol. This implies that the dominant mechanism involved is physical adsorption, with the notable exception of AC, which exhibits a chemisorption effect (Prarat *et al.,* 2018). The phenomenon of adsorption involves the transfer of mass, characterized by the attachment of a solute (adsorbate) to the solid surface of the adsorbent. This is achieved via

physisorption and chemisorption. Several factors impact the effectiveness of an adsorbent in absorbing materials. These include the adsorbent's composition, which involves aspects like pore size, functional groups, and structural characteristics, as well as the nature of the adsorbate, including its size, polarity, molecular weight, and functionality. Furthermore, the conditions under which the experiment is conducted, such as temperature and pH, are also critical (Srivastava *et al.,* 2021). Consequently, the previously mentioned results indicate that the pore size of biochar derived from Napier grass influences the adsorption of THMs and correlates with the size of the adsorbent. The physical absorption of energy E is below 4 kJ/mole. The interaction between the adsorbent and the adsorbing substance is characterized by weak energy interactions, especially those of the Van der Waals force type. Frequent use of adsorbed substances allows for easy separation, which can be followed by regeneration using methods such as thermal application or mechanical force (Larasati *et al.,* 2021). Enhancing the quality of the adsorbent can further improve adsorption efficiency. Particularly, the attachment of functional groups to charcoal raises the adsorbent's specific properties, as demonstrated in Induvesa *et al.* (2020). Furthermore, enhancing the quantity of mesopores leads to greater effectiveness in the treatment of various substances (Yimyam *et al.*, 2023; Siyasukh *et al.,* 2018). Upon availability of the sorbent post-disposal, it may be directed to landfills or designated safe storage or disposal facilities. According to Reddy *et al*. (2016), the closure of landfill sites and the practice of waste incineration contribute to the emergence of secondary pollution challenges. Incineration of DBPs sorbents has the potential to elevate toxic air pollution due to incomplete combustion processes. The act of recycling these materials may not yield a substantial effect on the environment. Further research must concentrate on the regeneration of Napier grass-derived adsorbents loaded with THMs. The cost analysis reveals that the price of batch experiments biochar synthesis, which is exposed to pretreatment before combustion with three specific chemicals (N-Na=67.8 Baht (THB)/kg, N-A=111.9 THB/kg, N-Fe=398.8 THB/kg), is higher than that of charcoal produced from untreated Napier grass (N-C=14 THB/kg). The adsorbent derived from Napier grass could be significant for production processes that utilize LPG, particularly in terms of cost efficiency. It produces a lower volume of pyrolyzed waste gases when compared to traditional methods. Further examination of significant issues in cost estimation research, particularly regarding cost synthesis, operating expenses, and elimination costs, is essential for future research. Considering the price comparison of adsorbent derived from corn cobs with pre-treatment using H_3PO_4, the value shown 134.7 THB/kg (Sriboonnak, 2019). Activated carbon may be priced at a maximum of 2590.0 THB/kg (Yimyam *et al.*, 2023). Thus, Potential applications for Napier grass biomass include its use as a filtration column aimed at reducing THMs in tap water. Findings from Sriboonnak *et al.* (2021) indicated that there were heightened levels of THMs contamination in tap water. At a concentration of 60 µg/L, the water complies with the limits set by the WHO. The accumulation of these substances has the potential to induce cancer. The analysis of expenses associated with energy consumption and biochar production is essential. The presence of additional pollutants in the treated water source or fluctuations in pH levels may diminish the effectiveness of adsorption.

CONCLUSION

There is growing attention on the potential interactions between substantial residues of disinfectants and organic compounds present in water. Its toxicity to internal systems occurs when ingested in high quantities or accumulated. The aim of this study was to determine the highly effective THM removal efficiency of Napier grass-derived adsorbent. The prepared materials were modified on the surface by chemical pretreatment, including $Fe(NO3)_3$, H_3PO_4, and NaOH, respectively. The production of the adsorbent from Napier grass involves a pyrolysis process, where the furnace is heated by introducing exhausted gases, with the addition of LPG to improve the overall efficiency of the procedure. Napier grass was effectively modified into adsorbents at a pyrolysis temperature of 600 °C for 1 h. The pyrolysis temperature of 600 °C affected the hydrocarbon content of biochar. A comprehensive analysis of low molecular weight organic constituents is essential. This has an impact on carbon formation, the key constituent of biochar, thus increasing the efficacy of THM adsorption. Additionally, Napier grass pieces underwent a 2 h pretreatment at 80°C in solutions comprising 0.2M H_3PO_4, 0.2M NaOH, and 0.05M $Fe(NO_3)$. The research studies chemically pretreated

adsorbents derived from Napier grass (N-C, N-Fe, N-A, N-Na) for the removal of trihalomethanes. SEM analysis revealed that the adsorbents had an irregular morphology with rough surfaces, a consequence of the pyrolysis and pretreatment processes. Analysis of the elements showed the presence of carbon, oxygen, potassium, and trace elements (Fe, Na, and P) on the surfaces of the adsorbent, which contribute to the enhancement of THM removal. The results of the XRD analysis indicated that the structures were primarily amorphous, with only a few crystalline regions present, which relates to their adsorptive characteristics. Chemical pretreatment enhanced carbon yield, with H_3PO_4 pretreatment achieving 43.8% owing to the facilitation of biopolymer rearrangement. The PZC was determined using a dose at 0.1 g/L in a 100 mL solution at room temperatura for 24 h. The surface charges of the adsorbent ranged from 7.5 to 10.0, suggesting that variations in the pH of the solution influenced the adsorption processes. Experiments conducted with high-dose adsorbent (dose range = 0.5-3.0 g/L, concentration at 100 µg/L in a 100 mL solution at room temperatura for 6 h) showed that N-A effectively removed 94.43% of THM at a concentration of 3 g/L. However, the use of high doses resulted in agglomeration, thereby decreasing overall efficiency. Furthermore, the characterization of these adsorbents was conducted by Type-I and Type-IV N_2 adsorption-desorption isotherm analyses, indicating a predominance of microporous characteristics with some mesoporous details. Contact time variations ranging from 0 to 24 hours (dose=0.2 g/L, concentration at 100 µg/L in a 100 mL solution, and maintained at room temperature) were conducted to investigate the kinetics of THM adsorption. The field of adsorption includes three primary kinetic models: pseudo-first order, pseudo-second order, and intraparticle diffusion. Furthermore, to determine the adsorption isotherm, the THM concentration was adjusted from 50 to 1000 µg/L in a 100 mL solution maintained at room temperature, with a dosage of 0.2 g/L. Four adsorption isotherm models—linear, Langmuir, Freundlich, and Dubinin-Radushkevich (D-R)—were applied to evaluate THM adsorption on adsorbents. A removal rate of 94.43% was attained at an N-A dosage of 3 g/L, despite N-A having a specific surface area that was inferior to that of AC. Adsorption kinetics followed a pseudo-second-order model, suggesting chemisorption as the dominant mechanism. N-A exhibited superior THM adsorption despite its lower surface area, indicating the significance of surface chemistry over physical attributes. The findings from equilibrium studies indicated that the adsorption capacities were between 566.72 and 605.88 µg/g, with DBM and BDCM showing a stronger affinity for the adsorbents. The Langmuir isotherm model efficiently characterized adsorption on adsorbents derived from Napier grass (R^2 = 0.948-0.998), indicating monolayer adsorption, whereas activated carbon demonstrated multilayer adsorption as described by the Freundlich model (R^2 = 0.998 for THM removal). The diffusion of pores involves a crucial role in the adsorption process for the THM species. The viability of chemically pretreated Napier grass adsorbents as economical and environmentally friendly solutions for THMs removal is determined by factors such as the pretreatment conditions, the configuration of the pore structure, and the underlying adsorption mechanisms. It is essential to conduct additional studies to determine the effectiveness of this adsorbent in real-world scenarios, where different variables may affect its performance. Improve operational efficiency through the reduction of environmental influences. Additionally, regeneration studies should assess the potential for further use of spent adsorbents.

AUTHOR CONTRIBUTIONS

A. Wongrueng, the corresponding author, has contributed to supervising, conceptualization, data analysis, and writing—review and editing. S. Sriboonnak prepared in data curation, methodology, experimental studies, data analysis, and the preparation of the original draft. P. Rakruam has performed review and editing. S. Nitayavardhana has contributed to review, and editing. A. Siyasukh has conducted review and editing. B. Sawangjang has performed review and editing. P. Induvesa has prepared the data analysis, review and editing. S. Takizawa has contributed to supervising, reviewing, and editing. All authors commented on previous versions of the manuscript and read and approved the final manuscript.

ACKNOWLEDGEMENT

The authors thank Chiang Mai University for the teaching assistant and research assistant scholarships to Miss Sornsiri Sriboonnak. Additionally, this work was supported by the Faculty of Engineering,

Chiang Mai University. The authors also thank the Department of Urban Engineering, the University of Tokyo, Japan. We would like to express our sincere gratitude to the Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University for invaluable support in terms of facilities and scientific equipment.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
% yield C	The carbon yield percentage
%removal	Percentage removal
°C	Degrees Celsius
1/n	The adsorption intensity
2θ	Bragg's angle
β	The constant of Dubinin-Radushkevich isotherm adsorption model
ε	The Polanyi potential of D-R isotherm adsorption model
µg/L	Microgram per lite
µm	Micrometer
AC	Activated carbon
BDCM	Bromodichloromethane
BET	Brunauer–Emmett–Teller adsorption
BF	Bromoform
BJH	Barrett, Joyner, and Halenda method
C	Carbon
C	The intercept constant that relates to the thickness of the boundary layer
Ca	Calcium
C_e	The equilibrium concentration
CF	Chloroform
C_f	Final concentration of THMs
C_i	Initial concentration of THMs
Cl	Chlorine
cm	Centimeter
cm^3/g	Cubic centimeter per gram
CO	Carbon monoxide
CO_2	Carbon dioxide
Cu Kα	X-ray energy frequently used on lab scale x-ray instrument
DBCM	Dibromochloromethane
DBPs	Disinfection by-products
DC	Sourced of activated carbon from DC Fine Chemicals Limited
DOM	Dissolved organic matter
D_p	Mean pore diameter of adsorbent
D-R	Dubinin and Radushkevich isotherm models
E	The mean free adsorption energy
ECD	An electron capture detector
EDX	Energy-dispersive x-ray spectroscopy
Eq.	Equation
Fe	Iron
$Fe(NO3)_3$	Ferric nitrate

$FeCl_3$	Ferric chloride
FESEM	Field emission scanning electron microscope
g	Gram
GC	Gas chromatograph
g/L	Gram per liter
h	Initial adsorption rate at t = 0
h	Hour
H_3PO_4	Phosphoric acid
HAAs	Haloacetic acids
HANs	Haloacetonitriles
HCl	Hydrochloric acid
i.e.	In other words
IUPAC	The international union of pure and applied chemistry
K	Kelvin or potassium
k	The intra-particle diffusion rate constant
k_1	The pseudo-first order rate constant
k_2	The pseudo-second order rate constant
K_f	The constant of Freundlich isotherm adsorption model
Kg	Kilogram
kJ/mol	Kilojules per mole
k_p	The constant of linear isotherm adsorption model
k_{p1}	The boundary diffusion rate constant
k_{p2}	The measured pore diffusion rate constant
LPG	Liquefied petroleum gas
L/mg/m	Lite per miligram per meter
M	Molar
mL	Milliliter
mm	Millimeter
mM	Millimole
MTBE	Methyl tertiary butyl ether
m^2/g	Square meter per gram
N_2	Nitrogen gas
Na	Sodium
NaOH	Sodium hydroxide
N-A	Napier grass-derived adsorbents were pretreatment with H_3PO_4
N-C	Napier grass-derived adsorbents with non-treatment
N-Fe	Napier grass-derived adsorbents were pretreatment with $Fe(NO_3)_3$
N-Na	Napier grass-derived adsorbents were pretreatment with NaOH
nm	Nanometer
O	Oxygen
pH_{final}	The final potential of hydrogen for point of zero charge
$pH_{initial}$	The initial pH of point of zero charge
PZC	The points of zero charge
q_{DR}	The theoretical isotherm saturation capacity
q_e	The adsorption capacity at the equilibrium
q_t	The adsorption capacity at time
rpm	Rounds per minute
S	Phosphorus
SEM	Scanning electron microscopy
Si	Silicon
S_{mic}	Micropore surface
SUVA	The specific ultraviolet absorbance
t	Time
$t_{1/2}$	Half-life time
Temp	Temperature
THB	Thai baht
THMs	Trihalomethanes
USEPA	The United States Environmental Protection Agency
VF-X	Capillary column phase in gas chromatography column
V_{mic}	Microporous volume
V_{tot}	Total pore volume
WHO	World Health Organization
XRD	X-ray diffraction
$ZnCl_2$	Zinc chloride

REFERENCES

Adesemuyi, M.F.; Adebayo, M.A.; Akinola, A.O.; Olasehinde, E.F.; Adewole, K.A.; Lajide, L., (2020). Preparation and characterisation of biochars from elephant grass and their utilisation for aqueous nitrate removal: Effect of pyrolysis temperature. J. Environ. Chem. Eng., 8(6): 104507 (**12 pages**).

Ahmedna, M.; Marshall, W.E.; Husseiny, A.A.; Rao, R.M.; Goktepe, I., (2004). The use of nutshell carbons in drinking water filters for removal of trace metals. Water Res., 38(4): 1062–1068 (**7 pages**).

Ali, S.I.; Arnold, M.; Liesner, F.; Fesselet, J.F., (2019). Characterization of disinfection by-products levels at an emergency surface water treatment plant in a refugee settlement in Northern Uganda. Water. 11(4): 647 (**12 pages**).

Bond, T.; Goslan, E.H.; Jefferson, B.; Roddick, F.; Fan, L.; Parsons, S.A., (2009). Chemical and biological oxidation of NOM surrogates and effect on HAA formation. Water Res., 43(10): 2615–2622 (**8 pages**).

Boon, T.H.; Raheem, A.; Ghani, W.A.W.A.K.; Hussain, S.A.; Sum, D.N.K., (2017). Thermogravimetric study of napier grass in inert and oxidative atmospheres conditions. J. Phys. Sci., 28(Suppl. 1): 155–169 **(15 pages)**.

Bridgwater, A., (2012). Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenergy. 38: 68–94 **(27 pages)**.

Chen, C.; Zhang, X.; He, W.; Lu, W.; Han, H., (2007), Comparison of seven kinds of drinking water treatment processes to enhance organic material removal: A pilot test. Sci. Total Environ., 382(1): 93–102. (**10 pages**).

Czajczyńska, D.; Anguilano, L.; Ghazal, H.; Krzyżyńska, R.; Reynolds, A.; Spencer, N.; Jouhara, H., (2017). Potential of pyrolysis processes in the waste management sector. Therm. Sci. Eng. Prog., 3: 171–197 **(27 pages)**.

Danish, M.; Ahmad, T.; Nadhari, W.N.A.W.; Ahmad, M.; Khanday, W.A.; Ziyang, L.; Pin, Z., (2018). Optimization of banana trunk-activated carbon production for methylene blue-contaminated water treatment. Appl. Water Sci., 8(1) **(11 page)**.

Da Silva Veiga, P.A.; Schultz, J.; Da Silva Matos, T.T.; Fornari, M.R.; Costa, T.G.; Meurer, L., (2020). Production of high-performance biochar using a simple and low-cost method: Optimization of pyrolysis parameters and evaluation for water treatment. J. Anal. Appl. Pyrolysis., 148: 104823 **(12 pages)**.

Deeudomwongsa, P.; Phattarapattamawong, S.; Lin, K.Y.A., (2017). Control of disinfection byproducts (DBPs) by ozonation and peroxone process: Role of chloride on removal of DBP precursors. Chemosphere., 184: 1215–1222 **(8 pages)**.

Di Blasi, C.; Galgano, A.; Branca, C., (2009). Effects of potassium hydroxide impregnation on wood pyrolysis. Energ Fuel. 23(2): 1045–1054 **(10 pages)**.

Dong, H.; Qiang, Z.; Richardson, S.D., (2019). Formation of iodinated disinfection byproducts (I-DBPs) in drinking water: Emerging concerns and current issues. Acc. Chem. Res., 52(4): 896–905 **(10 pages)**.

Fan, M.; Shao, Y.; Wang, Y.; Sun, J.; He, H.; Guo, Y.; Zhang, S.; Wang, S.; Li, B.; Hu, X., (2024). Evolution of pore structure and functionalities of activated carbon and phosphorous species in activation of cellulose with H_3PO_4. Renew. Energy. 122151 **(14 pages)**.

FAO, E., (1985). Industrial charcoal making. FAO Forestry Paper. Rome, Food and Agriculture Organization of the United Nations, 63.

He, C.; Kuo, Y.; Li, S., (2017). Lignocellulosic butanol production from Napier grass using semi-simultaneous saccharification fermentation. Bioresour. Technol., 231: 101–108 **(8 pages)**.

Hong, H.; Yan, X.; Song, X.; Qin, Y.; Sun, H.; Lin, H., (2017). Bromine incorporation into five DBP classes upon chlorination of water with extremely low SUVA values. Sci. Total Environ., 590–591: 720–728 **(9 pages)**.

Hung, Y.; Waters, B.W.; Yemmireddy, V.K.; Huang, C., (2017). pH effect on the formation of THM and HAA disinfection byproducts and potential control strategies for food processing. J. Integr. Agric., 16(12): 2914–2923 **(10 pages)**.

Induvesa, P.; Ratanatawanate, C.; Wongrueng, A.; Punyapalakul, P., (2020). Adsorption of iodinated trihalomethanes onto thiol functionalized ZIF-8s: Active adsorption sites, adsorptive mechanisms, and dehalogenation by-products. Sci. Total Environ., 754: 142376 (**15 pages**).

Kearns, J.P.; Shimabuku, K.K.; Mahoney, R.B.; Knappe, D.R.U.; Summers, R.S., (2015). Meeting multiple water quality objectives through treatment using locally generated char: improving organoleptic properties and removing synthetic organic contaminants and disinfection by-products. J. Water Sanit. Hyg. Dev., 5(3): 359–372 **(14 pages)**.

Kers, J.; Kulu, P.; Aruniit, A.; Laurmaa, V.; Križan, P.; Šooš, L.; Kask, Ü., (2010). Determination of physical, mechanical and burning characteristics of polymeric waste material briquettes. Proc. Est. Acad. Sci., 16(4): 307 **(11 pages)**.

Khan, A.H.; Khan, N.A.; Ahmed, S.; Dhingra, A.; Singh, C.P.; Khan, S.U.; Mohammadi, A.A.; Changani, F.; Yousefi, M.; Alam, S.; Vambol, S.; Vambol, V.; Khursheed, A.; Ali, I., (2020). Application of advanced oxidation processes followed by different treatment technologies for hospital wastewater treatment. J. Clean. Prod., 269: 122411 **(14 pages)**.

Kralles, Z.T.; Ikuma, K.; Dai, N., (2020). Assessing disinfection byproduct risks for algal impacted surface waters and the effects of peracetic acid pre-oxidation. Environ. Sci.: Water Res. Technol., 6(9): 2365–2381 **(17 pages)**.

Ifa, L.; Yani, S.; Nurjannah, N., Darnengsih, D.; Rusnaenah, A.; Mel, M.; Mahfud, M.; Kusuma, H.S., (2020). Techno-economic analysis of bio-briquette from cashew nut shell waste. Heliyon. 6(9): e05009 **(9 pages)**.

Larasati, A.; Fowler, G.D.; Graham, N.J., (2021). Insights into chemical regeneration of activated carbon for water treatment. J. Environ. Chem. Eng., 9(4): 105555 **(11 pages)**.

Liu, Q.S.; Zheng, T.; Wang, P.; Jiang, J.P.; Li, N., (2009).

Adsorption isotherm, kinetic and mechanism studies of some substituted phenols on activated carbon fibers. Chem. Eng. J., 157(2–3): 348–356 **(9 pages)**.

Liu, S.L.; Wang, Y.N.; Lu, K.T., (2014). Preparation and pore characterization of activated carbon from Ma bamboo (*Dendrocalamus latiflorus*) by H_3PO_4 chemical activation. J. Porous Mater., 21(4): 459–466 **(8 pages)**.

Liu, Z.; Sun, Y.; Xu, X.; Meng, X.; Qu, J.; Wang, Z., (2020). Preparation, characterization and application of activated carbon from corn cob by KOH activation for removal of Hg(II) from aqueous solution. Bioresour. Technol., 306: 123154 **(6 pages)**.

Lu, P.; Wang, X.; Tang, Y.; Ding, A.; Yang, H.; Guo, J.; Cui, Y.; Ling, C., (2020). Granular activated carbon assisted nitrate-dependent anaerobic methane oxidation-membrane bioreactor: Strengthening effect and mechanisms. Environ. Int., 138: 105675 **(10 pages)**.

Malik, R.; Goyal, A.; Yadav, S.; Gupta, N.; Goel, N.; Kaushik, A.; Kumar, V.; Tikoo, K.; Singhal, S., (2018). Functionalized magnetic nanomaterials for rapid and effective adsorptive removal of fluoroquinolones: Comprehensive experimental cum computational investigations. J. Hazard. Mater., 364: 621–634 **(14 pages)**.

Manasfi, T.; Coulomb, B.; Boudenne, J.L., (2017). Occurrence, origin, and toxicity of disinfection byproducts in chlorinated swimming pools: An overview. Int. J. Hyg. Environ. Health., 220(3): 591–603 **(12 pages)**.

Matsui, Y.; Nakao, S.; Sakamoto, A.; Taniguchi, T.; Pan, L.; Matsushita, T., (2015). Adsorption capacities of activated carbons for geosmin and 2-methylisoborneol vary with activated carbon particle size: Effects of adsorbent and adsorbate characteristics. Water Res., 85: 95–102 **(7 pages)**.

Mazlan, M.A.F.; Uemura, Y.; Yusup, S.; Elhassan, F.; Uddin, A.; Hiwada, A., (2016). Activated carbon from rubber wood sawdust by carbon dioxide activation. Procedia Eng., 148: 530–537 **(8 pages)**.

Meyer, S.; Glaser, B.; Quicker, P., (2011). Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environ. Sci. Technol., 45(22): 9473–9483 **(11 pages)**.

Mohammed, I.Y.; Abakr, Y.A.; Kazi, F.K.; Yusuf, S.; Alshareef, I.; Chin, S.A., (2015). Pyrolysis of Napier grass in a fixed bed reactor: Effect of operating conditions on product yields and characteristics. BioRes. 10(4): 6457-6478 **(22 pages)**.

Mohammed, I.Y.; Abakr, Y.A.; Yusup, S.; Kazi, F.K., (2016). Valorization of Napier grass via intermediate pyrolysis: Optimization using response surface methodology and pyrolysis products characterization. J. Clean. Prod., 142: 1848–1866 **(19 pages)**.

Muniandy, L.; Adam, F.; Mohamed, A.R.; Ng, E.P., (2014). The synthesis and characterization of high purity mixed microporous/mesoporous activated carbon from rice husk using chemical activation with NaOH and KOH. Microporous Mesoporous Mater., 197: 316–323 **(8 pages)**.

Nakanishi, K., (2006). Sol–Gel process of oxides accompanied by phase separation. Bull. Chem. Soc. Jpn.,79(5): 673–691 **(19 pages)**.

Nantasaksiri, K.; Charoen-Amornkitt, P.; Machimura, T. (2021)., Integration of multicriteria decision analysis and geographic information system for site suitability assessment of Napier grass-based biogas power plant in southern Thailand. Renew. Sustain. Energy Transit., 100011 **(12 pages)**.

Nath, H.; Saikia, A.; Goutam, P.J.; Saikia, B.K.; Saikia, N., (2021). Removal of methylene blue from water using okra (*Abelmoschus esculentus* L.) mucilage modified biochar. Bioresour. Technol. Rep., 14: 100689 **(10 pages)**.

Office of Water, (2016). Title of subordinate document. In: Six-Year review 3 technical support document for disinfectants/disinfection byproducts rule. Available via DIALOG. https://www.epa.gov/sites/production/files/2016-12/documents/810r16012.pdf. Accessed on 25 October 2024.

Onchieku, J.; Chikamai, B.; Rao., (2012). Optimum parameters for the formulation of charcoal briquettes using bagasse and clay as binder. Eur. J. Sustainable Dev., 1(3): 477 **(16 pages)**.

Park, B.; Cho, E.; Son, Y.; Khim, J., (2014). Distribution of electrical energy consumption for the efficient degradation control of THMs mixture in sonophotolytic process. Ultrason. Sonochem., 21(6): 1982–1987 **(6 pages)**.

Pinky, N.S.; Mobarak, M.B.; Mustafi, S.; Rahman, M.Z.; Nahar, A.; Saha, T., (2023). Facile preparation of micro-porous biochar from Bangladeshi sprouted agricultural waste (corncob) via in-house built heating chamber for cationic dye removal. Arab. J. Chem., 16(9): 105080 **(18 pages)**.

Plewa, M.J.; Muellner, M.G.; Richardson, S.D.; Fasano, F.; Buettner, K.M.; Woo, Y.T., (2007). Occurrence, synthesis, and mammalian cell cytotoxicity and genotoxicity of haloacetamides: an emerging class of nitrogenous drinking water disinfection byproducts. Environ. Sci. Technol., 42(3): 955–961 **(7 pages)**.

Poleneni, SR., (2020). Global disinfection by-products regulatory compliance framework overview, disinfection by-products in drinking water: detection and treatment. In: Elsevier eBooks., 305–335 **(31 pages)**.

Prarat, P.; Ngamcharussrivichai, C.; Khaodhiar, S.; Punyapalakul, P., (2018). Adsorption of single and mixed haloacetonitriles on silica-based porous materials: Mechanisms and effects of porous structures. J. Environ. Sci., 79: 346–360 **(15 pages)**.

Premchand, P.; Demichelis, F.; Galletti, C.; Chiaramonti, D.; Bensaid, S.; Antunes, E.; Fino, D., (2024). Enhancing biochar production: A technical analysis of the combined influence of chemical activation (KOH and NaOH) and pyrolysis atmospheres (N_2/CO_2) on yields and properties of rice husk-derived biochar. J. Environ. Manage., 370: 123034 **(12 pages)**.

Qin, J.; Wang, J.; Long, J.; Huang, J.; Tang, S.; Hou, H.; Peng, P., (2022). Recycling of heavy metals and modification of

biochar derived from Napier grass using HNO_3. J. Environ. Manage., 318: 115556 **(9 pages)**.

Ratpukdi, T.; Sinorak, S.; Kiattisaksiri, P.; Punyapalakul, P.; Siripattanakul-Ratpukdi, S., (2019). Occurrence of trihalomethanes and haloacetonitriles in water distribution networks of Khon Kaen Municipality, Thailand. Water Sci. Technol.: Water Supply, 19(6): 1748–1757 **(10 pages)**.

Reddy, D.H.K.; Vijayaraghavan, K.; Kim, J.A.; Yun, Y., (2016). Valorisation of post-sorption materials: Opportunities, strategies, and challenges. Adv. Colloid Interface Sci., 242: 35–58 **(24 pages)**.

Ren, B.; Zhang, X.; An, H.; Ding, S.; Zhang, H.; Zeng, X., (2023). Hollow cotton carbon based $NiCo_2S_4$/$NiMoO_4$ hybrid arrays for high performance supercapacitor. J. Energy Storage, 59: 106553 **(10 pages)**.

Reza, M.S.; Islam, S.N.; Afroze, S.; Bakar, M.S.A.; Sukri, R.S.; Rahman, S.; Azad, A.K., (2019). Evaluation of the bioenergy potential of invasive Pennisetum purpureum through pyrolysis and thermogravimetric analysis. Energy Ecol. Environ., 5(2): 118–133 **(16 pages)**.

Rook, J.J., (1974). Formation of Haloforms during Chlorination of Natural Waters. Water Treatment and Examination, 23: 234–243 **(10 pages)**.

Semerjian, L., (2010). Equilibrium and kinetics of cadmium adsorption from aqueous solutions using untreated Pinus halepensis sawdust. J. Hazard. Mater., 173(1–3):236–242 **(7 pages)**.

SEPA Method, (1995). Title of subordinate document. In: Determination of chlorination disinfection byproducts, chlorinated solvents and halogenated pesticides/herbicides in drinking water by liquid-liquid extraction and gas chromatography with electron capture detection; Revision 1.0; U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory: Cincinnati, OH, USA. Available via DIALOG.

Shaaban, A.; Se, S.M.; Mitan, N.M.M.; Dimin, M.F., (2013). Characterization of biochar derived from rubber wood sawdust through slow pyrolysis on surface porosities and functional groups. Procedia Eng., 68: 365–371 **(7 pages)**.

Shi, Y.; Liu, G.; Wang, L.; Zhang, H., (2019). Heteroatom-doped porous carbons from sucrose and phytic acid for adsorptive desulfurization and sulfamethoxazole removal: A comparison between aqueous and non-aqueous adsorption. J. Colloid Interface Sci., 557: 336–348 **(13 pages)**.

Simões, V.D.N.; Brasil, J.A.; De Sousa, J.F.; Lopes Moriyama, A.L.; Braga, A.D.N.S.; De Oliveira, T.F., (2023). Physico-chemical modification of elephant grass (Pennisetum purpureum) by steam explosion and surfactant impregnation for Cr (III) adsorption. Braz. J. Chem, 41(1): 487–504 **(18 pages)**.

Sing, K.S.W., (1982). Reporting physisorption data for gas/solid systems with special reference to the determination of surface area and porosity (Provisional). Pure Appl. Chem., 54(11): 2201–2218 **(18 pages)**.

Siyasukh, A.; Chimupala, Y.; Tonanon, N., (2018). Preparation of magnetic hierarchical porous carbon spheres with graphitic features for high methyl orange adsorption capacity. Carbon, 134: 207–221 **(15 pages)**.

Song, M.; Jin, B.; Xiao, R.; Yang, L.; Wu, Y.; Zhong, Z., (2013). The comparison of two activation techniques to prepare activated carbon from corn cob. Biomass Bioenergy, 48: 250–256 **(7 pages)**.

Srivastava, A.; Gupta, B.; Majumder, A.; Gupta, A.K.; Nimbhorkar, S.K., (2021). A comprehensive review on the synthesis, performance, modifications, and regeneration of activated carbon for the adsorptive removal of various water pollutants. Environ. Chem. Eng., 9(5): 106177 **(29 pages)**.

Sriboonnak, S.; Induvesa, P.; Wattanachira, S.; Rakruam, P.; Siyasukh, A.; Pumas, C., Wongrueng, A.; Khan, E., (2021). Trihalomethanes in water supply system and water distribution networks. Int. J. Environ. Res. Public Health, 18(17): 9066 **(12 pages)**.

Sriboonnak, S., (2019). Title of subordinate document. In: Utilization of carbon dioxide from pyrolysis process and phosphoric acid on synthesis of activated carbon from corncob. Dissertation in Environmental Engineering. Faculty of Engineering. Chiang Mai University, Chiang Mai, Thailand.

Teng, H.; Yeh, T.S.; Hsu, L.Y., (1998). Preparation of activated carbon from bituminous coal with phosphoric acid activation. Carbon, 36(9): 1387–1395 **(9 pages)**.

Thokchom, B.; Radhapyari, K.; Dutta, S., (2020). Occurrence of trihalomethanes in drinking water of Indian states: a critical review. Elsevier eBooks, 83–107 **(25 pages)**.

Tongpoothorn, W.; Sriuttha, M.; Homchan, P.; Chanthai, S.; Ruangviriyachai, C., (2010). Preparation of activated carbon derived from Jatropha curcas fruit shell by simple thermo-chemical activation and characterization of their physico-chemical properties. Process Saf. Environ. Prot., 89(3): 335–340 **(6 pages)**.

Tsai, M.; Lee, W.; Kuan, W.; Sirisansaneeyakul, S.; Savarajara, A., (2018). Evaluation of different pretreatments of Napier grass for enzymatic saccharification and ethanol production. Energy Sci. Eng., 6(6): 683–692 **(10 pages)**.

Tugulea, A.M.; Aranda Rodriguez, R.; Bérubé, D.; Giddings, M.; Lemieux, F.; Hnatiw, J., (2017). The influence of precursors and treatment process on the formation of Iodo-THMs in Canadian drinking water. Water Res., 130: 215–223 **(9 pages)**.

Vargas, A.C.G.; Dresch, A.P.; Schmidt, A.R. Tadioto, V.; Giehl, A.; Fogolari, O.; Mibielli, G.M.; Alves, S. L.; Bender, J.P., (2023). Batch fermentation of lignocellulosic elephant grass biomass for 2G ethanol and xylitol production. Bioenerg Res., 16(4): 2219–2228 **(10 pages)**.

Wang, Q.; Yu, Y.; Li, Y.; Min, X.; Zhang, J.; Sun, T., (2021). Methane separation and capture from nitrogen rich gases by selective adsorption in microporous Materials: A review. Sep. Purif. Technol., 283: 120206 **(18 pages)**.

Wang, X.; Zhao, Y.; Deng, J.; Zhou, Y.; Yuan, S., (2023). Study

on the influence mechanism of mineral components in biochar on the adsorption of Cr(VI). Fuel, 340: 127631 **(14 Pages)**.

WHO, (2011). Guidelines for drinking water quality, 4th ed.; World Health Organization: Geneva, Switzerland.

Xu, Z.; Tian, D.; Sun, Z.; Zhang, D.; Zhou, Y.; Chen, W., (2019). Highly porous activated carbon synthesized by pyrolysis of polyester fabric wastes with different iron salts: Pore development and adsorption behavior. Colloids Surf. A: Physicochem. Eng. Asp., 565: 180–187 **(8 pages)**.

Yeh, R.H.; Lin, Y.S.; Wang, T.H.; Kuan, W.C.; Lee, W.C., (2016). Bioethanol production from pretreated Miscanthus floridulus biomass by simultaneous saccharification and fermentation. Biomass Bioenergy, 94: 110–116 **(7 pages)**.

Yimyam, K.; Wongrueng, A.; Rakruam, P., (2023). Haloacetonitriles adsorption using a low-cost adsorbent derived from canvas fabric. Environ. Res., 234: 116539 **(7 pages)**.

Zhao, X.; Huang, Z.; Sun, H.; Zhao, Q.; Huang, Z.; Zhang, C.; Wang, Y.; Yang, C.; Zhou, Z., (2024). Comparison on molecular transformation of dissolved organic matter during Fenton and activated carbon adsorption processes for chemical cleaning wastewater treatment. Sep. Purif. Technol., 344: 127226 **(11 Pages)**.

AUTHOR (S) BIOSKETCHES

Sriboonnak, S., Ph.D. Candidate of Engineering Program in Environmental Engineering, Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand.
- Email: *Sornsiri_sri@cmu.ac.th*
- ORCID: 0009-0001-4220-4883
- Web of Science ResearcherID: NA
- Scopus Author ID: 57208056402
- Homepage: https://www.researchgate.net/scientific-contributions/Sornsiri-Sriboonnak-2200243173

Wongrueng, A., Ph.D., Associate Professor, Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand.
- Email: *aunnop@eng.cmu.ac.th*
- ORCID: 0000-0001-9180-3949
- Web of Science ResearcherID: NA
- Scopus Author ID: 36160066500
- Homepage: https://www.researchgate.net/scientific-contributions/Aunnop-Wongrueng-65461

Rakruam, P., Ph.D., Assistant Professor, Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand.
- Email: *pharkphum@eng.cmu.ac.th*
- ORCID: 0000-0001-9198-4655
- Web of Science ResearcherID: NA
- Scopus Author ID: 56061033700
- Homepage: https://www.researchgate.net/profile/Pharkphum-Rakruam-2

Nitayavardhana, S., Ph.D., Assistant Professor, Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand.
- Email: *saoharit@eng.cmu.ac.th*
- ORCID: 0009-0003-6339-6735
- Web of Science ResearcherID: NA
- Scopus Author ID: 25225721800
- Homepage: https://www.researchgate.net/profile/Saoharit-Nitayavardhana

Sittisom, P., Ph.D., Assistant Professor, Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand.
- Email: *prattakorn.s@cmu.ac.th*
- ORCID: 0009-0003-9839-6604
- Web of Science ResearcherID: NA
- Scopus Author ID: 57876690500
- Homepage: https://www.researchgate.net/profile/Prattakorn-Sittisom

Siyasukh, A., Ph.D., Assistant Professor, Department of Industrial Chemistry, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand.
- Email: *adisak.si@cmu.ac.th*
- ORCID: 0000-0003-0819-2257
- Web of Science ResearcherID: NA
- Scopus Author ID: 8721606800
- Homepage: https://www.researchgate.net/profile/Adisak-Siyasukh

AUTHOR (S) BIOSKETCHES

Induvesa, P., Ph.D., Researcher, Department of Environmental science, Faculty of Science, Silpakorn University, Nakhon Pathom 73000, Thailand
- Email: *induvesa_p@su.ac.th*
- ORCID: 0000-0003-1737-1724
- Web of Science ResearcherID: NA
- Scopus Author ID: 57219258865
- Homepage: https://www.researchgate.net/scientific-contributions/Phacharapol-Induvesa-2186927229

Sawangjang, B., Ph.D., Project Research Associate, Department of Urban Engineering, Graduate School of Engineering, The University of Tokyo, Japan 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
- Email: *benyapa@env.t.u-tokyo.ac.jp*
- ORCID: 0000-0003-3287-299X
- Web of Science ResearcherID: NA
- Scopus Author ID: 57210826343
- Homepage: https://www.researchgate.net/profile/Benyapa-Sawangjang

Takizawa, S., Ph.D., Professor, Department of Urban Engineering, Graduate School of Engineering, The University of Tokyo, Japan 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
- Email: *takizawa@env.t.u-tokyo.ac.jp*
- ORCID: 0000-0001-6028-2327
- Web of Science ResearcherID: NA
- Scopus Author ID: 57234065300
- Homepage: https://www.researchgate.net/profile/Satoshi-Takizawa

HOW TO CITE THIS ARTICLE

Sriboonnak, S.; Wongrueng, A.; Rakruam, P.; Nitayavardhana, S.; Sittisom, P.; Siyasukh, A.; Induvesa, P.; Sawangjang, B.; Takizawa, S., (2025). Removal of trihalomethanes from activated Napier grass-derived adsorbent using liquefied gas and chemical pretreatment. Global J. Environ. Sci. Manage., 11(2): 365-390.

DOI: 10.22034/gjesm.2025.02.01

URL: https://www.gjesm.net/article_720559.html

Global J. Environ. Sci. Manage. 11(2): 391-402, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Optimized removal of trivalent arsenic from aquatic environments using *Prosopis juliflora* seed biomass

M. Samimi[1,*], J. Nouri[2,3]

[1]*Department of Chemical Engineering, Faculty of Engineering, Kermanshah University of Technology, Kermanshah, Iran*

[2]*Department of Environmental Health Engineering, Tehran University of Medical Sciences, Tehran, Iran*

[3]*1137 Spectrum, Irvine, Orange County 92618 USA*

ARTICLE INFO

Article History:
Received 14 October 2024
Revised 19 January 2025
Accepted 20 February 2025

Keywords:
Biomass
Biosorption
Metalloid uptake
Prosopis juliflora

ABSTRACT

BACKGROUND AND OBJECTIVES: With urban populations struggling with wastewater and water sources contaminated by metalloids, the demand for sustainable and effective methods for removing heavy metals is growing ever more urgent. Arsenic contamination in wastewater and water supplies is a critical environmental concern worldwide, posing severe health risks and demanding effective mitigation strategies. With numerous regions contending with increased arsenic levels, it is crucial to explore various removal strategies to maintain water quality and safeguard public health. Employing biomass obtained from waste materials offers an affordable and uncomplicated strategy for the removal of environmental pollutants. The study objectives were to evaluate the ability of biomass derived from ***Prosopis juliflora*** fruit to uptake arsenic from wastewater..

METHODS: Following the drying process, the harvested biosorbent was processed into a fine powder through grinding. All tests utilized the biomass that had been refined to powder sizes of less than 45 micrometers. An assessment of arsenic adsorption was conducted using response surface methodology, focusing on the effects of several operational parameters, including the biosorbent to arsenic ratio, solution potential of hydrogen, and the contact time between the biomass and the analyte. Additionally, the optimal conditions for maximizing arsenic removal by the biomass of ***Prosopis juliflora*** were determined through the Box-Behnken approach. Kinetic studies were conducted to statistically analyze the trivalent arsenic adsorption process.

FINDINGS: The effectiveness of the proposed model in identifying the optimal conditions for the trivalent arsenic uptake process was validated through testing. The analysis of experimental data revealed the coefficient of determination, adjusted coefficient, and predicted coefficient values to be 0.9936, 0.9820, and 0.9053, respectively. According to the results, the highest adsorption of arsenic ions by the biomass was achieved at 91.11 percentage, with ***Prosopis juliflora*** fruit biomass to-arsenic ratio of 8:1, potential of hydrogen of 7.5, and a contact time of 90 minutes.

CONCLUSION: The findings of this study indicate that the biomass of ***Prosopis juliflora*** fruit serves as an efficient sorbent for the removal of trivalent arsenic from water under optimal conditions. The adsorption data aligned with pseudo-second-order kinetics, with a maximum capacity of 114.94 milligrams per gram, suggesting that the adsorption of trivalent arsenic onto the ***Prosopis juliflora*** occurs in monolayers.

DOI: 10.22034/gjesm.2025.02.02

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
61	4	4

*Corresponding Author:
Email: *m.samimi@kut.ac.ir*
Phone: +989188365523
ORCID: 0000-0003-3098-7283

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

High concentrations of toxic metals, including cadmium, chromium, mercury, arsenic, lead, and zinc, are commonly found in industrial effluents, often exceeding the permissible limits in treated wastewater (Asadullah *et al*., 2022; Hawrami and Baset, 2024; Samimi and Shahriari Moghadam, 2024). Wastewater contamination poses a multifaceted challenge to public health and environmental sustainability (Mohadesi *et al*., 2024a; Samimi and Moghadam, 2024a). The water sources that serve urban areas, crucial for maintaining population health, are increasingly at risk of contamination from both anthropogenic influences and natural occurrences (Al-Azzawi and Saleh, 2023; Samimi and Validov, 2018). The detrimental impact of contaminated wastewater on public health necessitates a thorough investigation into the sources and potential remediation strategies (Samimi and Shahriari Moghadam, 2020; Ehzari *et al*., 2022). Water supplies are vulnerable to a diverse array of contaminants, ranging from microbial pathogens to chemical pollutants. The presence of pathogenic microorganisms, such as bacteria and viruses, raises concerns about waterborne diseases (Erdag *et al*., 2023). Moreover, the complexity of water and wastewater quality issues is exacerbated by the presence of heavy metals, industrial byproducts, and emerging contaminants, which include pharmaceuticals and personal care products (Sulistyowati *et al*., 2023; Sabilillah *et al*., 2023; Cheraghipoor *et al*., 2024). Advanced treatment technologies, including membrane filtration, activated carbon adsorption, and ultraviolet disinfection, offer effective means of removing diverse contaminants (Handayani *et al*., 2024; Abdallat *et al*., 2024; Fatima *et al*., 2024). Additionally, the implementation of green infrastructure, sustainable urban design, and community-focused programs can significantly aid in addressing contamination at its source (Douglas, 2018). The burgeoning demands of growing cities, coupled with the escalating threats of waterborne contaminants, necessitate continuous advancements in wastewater treatment methodologies (Mohadesi *et al*., 2024b). Arsenic, classified as a metalloid, consistently raises concerns regarding its presence in both water and wastewater. The main environmentally relevant forms include arsenite (As(III)), arsenate (As(V)), monomethylarsenate, and dimethylarsenate. Trivalent arsenic is typically more toxic than pentavalent arsenic. Arsenic contamination in water and wastewater sources is a significant worldwide challenge, endangering public health and demanding specific actions for successful removal (Samimi *et al*., 2023a). Arsenic, a naturally occurring element, often finds its way into water supplies through geological processes or human activities such as mining and industrial discharges (Hammond *et al*., 2018; Abubakar *et al*., 2023). Arsenic contamination, commonly stemming from natural geological formations or human-induced activities, emphasizes the essential demand for innovative technologies in water and wastewater treatment. Arsenic removal from water and wastewater due to toxicity and carcinogenicity is paramount (Younas *et al*., 2024). Municipal water systems, prone to arsenic infiltration due to geological conditions or industrial discharges, must implement effective arsenic removal techniques to satisfy demanding water quality criteria. The recognition of arsenic as a silent threat to public health has prompted a renewed focus on developing sustainable and efficient treatment methodologies (Phewnil *et al*., 2024). Copper smelting wastewater can contain high levels of arsenic, often in the form of As(III) (Luo *et al*., 2010). Paper mill industries can generate wastewater that contains arsenic (Zodi *et al*., 2011). Various treatment methods have been investigated for arsenic removal, including electrocoagulation using iron electrodes, which has shown effectiveness in treating both organic matter and arsenic salts in paper mill wastewaters (Balasubramanian and Madhavan, 2001). The challenge of arsenic removal stems from the presence of various oxidation states and the necessity for selective extraction to comply with strict regulatory standards (Nicomel *et al*., 2016). Conventional treatment methods, such as coagulation-flocculation, precipitation, and activated alumina adsorption, have shown efficacy, yet challenges persist in terms of cost-effectiveness and operational sustainability (Elhadeuf *et al*., 2023). Various biomass sources, including oil palm waste, algae, fungi, bacteria, and agricultural by-products, have demonstrated usage to produce biofuel (Osipova and Gladkov, 2024), usage to design and prepare stable catalysts (Goudarziafshar *et al*., 2024) and excellent adsorption capabilities for contaminants such as dyes, heavy metals, phenolic compounds, and petroleum pollutants (Vahabisani and An, 2021; Samimi and Nouri, 2023; Bakar *et*

al., 2024; Samimi and Shahriari-Moghadam, 2025). *Prosopis Juliflora* is a tree in the family Fabaceae. Found in semi-arid and arid regions worldwide, *Prosopis juliflora* is recognized as an invasive tree species (Yadav and Rana, 2020). It is a species of mesquite planted in most of the dry and hot regions of Africa, Australia, Asia (Eshetu *et al*., 2024; Rembold *et al*., 2015) and Ethiopia's Middle Awash area (Mehari, 2015). his plant reproduces through seeds and is cultivated in select regions to promote urban greening, stabilize loose sand, combat soil erosion, and function as a source of fuel and fodder, owing to its unique characteristics (Oliver Paul Nayagam and Prasanna, 2023; Gebrehiwot and Steger, 2024). *Prosopis juliflora* bears bean-shaped fruit in the summer which is not edible. Despite the extensive research conducted on the removal of arsenic using biosorbents, there has been no investigation into the effectiveness of *Prosopis juliflora* fruit biomass (PJB) in absorbing arsenic from wastewater. This study was performed to evaluate the ability of biomass obtained from *Prosopis juliflora* fruit for the arsenic uptake from wastewater. The operational factors in arsenic removal by PJB were also investigated and optimized. The current investigation has been performed in Kermanshah, Iran in 2024.

MATERIALS AND METHODS

Preparation of PJB biosorbent

The *Prosopis juliflora* fruit was collected from southern cities of Iran. The method of preparing biomass was executed based on research conducted by Samimi (2024). The collected biosorbents were washed using deionized water to eliminate surface impurities from the *Prosopis juliflora*. Subsequently, they were dried in an oven at a temperature of 32 degrees Celsius (°C) for a duration of 72 hours. After the drying stage, the adsorbent was pulverized into a fine powder and then subjected to sieving. The final PJB product, with particle sizes below 45 micrometers (µm), was applied in subsequent research endeavors.

Stock solution and batch biosorption

The As(III) stock solution (200 milligram per liter (mg/L)) was prepared by dissolving a certain amount of sodium arsenite salt ($Na_2HAsO_3{\cdot}5H_2O$) in double distilled water. The solutions for the experiments, each with distinct conditions, were prepared by diluting the stock solution accordingly. As outlined in the experimental design, the synthetic wastewater solution underwent vortexing and stirring for varying durations. The PJB-As(III) solution underwent centrifugation at 6000 Revolutions per minute (rpm) for 10 minutes (min) utilizing the Z205-A centrifuge model-USA (United States of America) to effectively separate any solid particles. The indirect assessment of As(III) ion adsorption involved measuring the concentration of the remaining metalloid in the supernatant using a flame-type atomic absorption spectrometer. The kinetics associated with the biosorption of As(III) by PJB were examined in batch systems at ambient temperature. The kinetics of As(III) biosorption by PJB was investigated in batch systems at ambient temperature. The removal of As(III) per gram of PJB and its uptake efficiency were determined using Eqs 1-3 (Samimi and Safari, 2022).

$$\text{Arsenic uptake efficiency: } \frac{(C_0 - C_e)\times 100}{C_0}\% \quad (1)$$

$$q_e = \frac{\mathrm{V}.(C_0 - C_e)}{M} \quad (2)$$

$$q_t = \frac{V}{M}(C_0 - C_t) \quad (3)$$

Where, q_e and q_t represent the PJB biosorption capacity measured in milligrams per gram (mg/g) at equilibrium and at time t (min). C_0 and C_e denote the initial and final concentrations of As(III) (mg/g). M indicates the dosage of PJB (g), while V refers to the volume of the As(III) solution (L).

Table 1: The experimental factors and the range of levels

Independent variables		Levels and ranges		
Operational parameters	Symbol	-1	0	+1
PJB-to-arsenic ratio	PA	2:1	5:1	8:1
pH of synthetic wastewater	pH	1.5	4.5	7.5
Contact time (min)	t	10	50	90

Table 2: The responses associated with three independent variables based on DOE

Run. no.	Operational variables			Response
	Y_{PA}	Y_{pH}	Y_t	As. R%
1	0	-1	1	18.14
2	-1	0	1	34.28
3	1	0	-1	39.55
4	0	0	0	34.89
5	0	-1	-1	13.36
6	1	0	1	69.20
7	0	0	0	37.82
8	0	1	1	80.23
9	1	-1	0	18.21
10	-1	0	-1	29.12
11	0	1	-1	61.82
12	-1	1	0	56.09
13	-1	-1	0	9.55
14	1	1	0	78.62
15	0	0	0	36.40

Design of experiments (DOE) and removal optimization

The Box Behnken design (BBD) was utilized in the study's design (using Minitab-18 software) to comprehensively assess the impact of independent variables and their interactions on the As(III) uptake from synthetic wastewater. The evaluation of optimal conditions for independent variables to maximize As(III) removal efficiency was conducted using response surface methodology (RSM) based on BBD (Aghajani *et al*., 2024; Kamaraj *et al*., 2024). The operating parameters listed in Table 1 were studied at three different levels, resulting in 15 runs that incorporated three center points. The independent variables examined included the ratio of PJB to arsenic (PA), the potential of hydrogen (pH) level of a synthetic wastewater solution containing arsenic ions, and the duration of contact time (t).

The results of DOE concerning the operating variables are presented in Table 2. A statistical analysis of the mathematical model was conducted, which included an analysis of variance (ANOVA) at a significance level of 5 percents (%) (Moghadam and Samimi, 2022; Ebrahimzadeh *et al*., 2024).

The full quadratic model illustrating the relationship between the amount of As(III) removal percentage (*As.R%*) and the response variables is represented by Eq. 4 (Samimi and Mansouri, 2024).

$$As.R\% = a_0 + \sum_{i=1}^{3} a_i Y_i + \sum_{i=1}^{3} a_{ii} Y_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} a_{ij} Y_{ij} \quad (4)$$

Where, Y_i and Y_{ij} are the encoded independent variable; a_0, a_i, α_{ii} and a_{ij} denote intercept, linear, second order and interaction terms, and *As.R%* is the response variable. As outlined in prior studies, the F-value calculated for evaluating the statistical significance of the models was determined accordingly (Samimi and Moghadam, 2024b).

RESULTS AND DISCUSSION

Model fitting and statistical analysis by BBD

The relationship between experimental conditions and arsenic uptake response was characterized by quadratic polynomial equations, which were derived from the statistical modeling of the experimental data (Samimi and Shahriari Moghadam, 2018). According to the statistical analysis based on BBD, the ultimate predicted model equation, in terms of coded factors, is represented in Eq. 5.

$$\begin{aligned} As.R\ \% = {} & 36.37 + 9.57\ Y_{PA} + 27.19\ Y_{pH} + 7.25\ Y_t \\ & + 1.95\ Y_{PA}^2 + 2.30\ Y_{pH}^2 + 4.72\ Y_t^2 + 3.47\ Y_{PA}.Y_{pH} \\ & + 6.12\ Y_{PA}.Y_t + 3.41\ Y_{pH}.Y_t \end{aligned} \quad (5)$$

The arsenic removal efficiency obtained from 15 experimental runs, varied between 9.55% and 80.23% as indicated in Table 2.

The ANOVA results for As(III) biosorption were analyzed to assess the validity and adequacy of the BBD model, and to determine the significance of the main parameters (Table 3). An elevated F-value, together with p-values under 0.05, demonstrates a more substantial significance for the factors being analyzed (Samimi *et al*., 2023b). Based on the results

shown in Table 3 the BBD model used in the study was significant with an F-value of 86.08 and a p-value less than 0.0001. All the coded terms of linear (Y_{PA}, Y_{pH}, and Y_t), one of the 2-way interaction term ($Y_{PA}.Y_t$), and one of the square term (Y_t^2) were significant, meaning their changes effectively describe As(III) adsorption onto PJB. The items with p-values greater than 0.05, (Y_{PA}^2,Y_{pH}^2, $Y_{PA}.Y_{pH}$, $Y_{pH}.Y_t$) were found to be non-significant. The removal of As(III) from synthetic wastewater, as well as the predicted values obtained from the full quadratic model, is depicted in Fig. 1, which is presented as a normal probability plot. The selected regression model has a coefficient of determination (R^2) value of 0.9936, which means that the independent studied variables explain 99.36% of the variation in arsenic uptake by PJB. A regression model exhibiting an R^2 value greater than 0.9 demonstrates a robust correlation. The predicted

Table 3: The ANOVA results of the reduced quadratic model for As(III) biosorption

Source	Degrees of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	F-Value	P-Value	Significant (✓) Not significant (×)
Regression	9	7414.51	823.83	86.08	< 0.001	✓
Linear	3	7066.08	2355.36	246.09	< 0.001	✓
Y_{PA}	1	732.30	732.30	76.51	< 0.001	✓
Y_{pH}	1	5913.28	5913.28	617.83	< 0.001	✓
Y_t	1	420.50	420.50	43.93	0.001	✓
Square	3	103.96	34.65	3.62	0.100	×
Y_{PA}^2	1	14.02	14.02	1.47	0.280	×
Y_{pH}^2	1	19.51	19.51	2.04	0.213	×
Y_t^2	1	82.22	82.22	8.59	0.033	✓
2-Way Interaction	3	244.48	81.49	8.51	0.021	✓
$Y_{PA}.Y_{pH}$	1	48.09	48.09	5.02	0.075	×
$Y_{PA}.Y_t$	1	149.94	149.94	15.67	0.011	✓
$Y_{pH}.Y_t$	1	46.44	46.44	4.85	0.079	×
Residual error	5	47.86	9.57			-
Lack-of-Fit	3	43.56	14.52	6.76	0.132	×
Pure Error	2	4.29	2.15	-	-	-
Total	14	7462.37	-	-	-	-

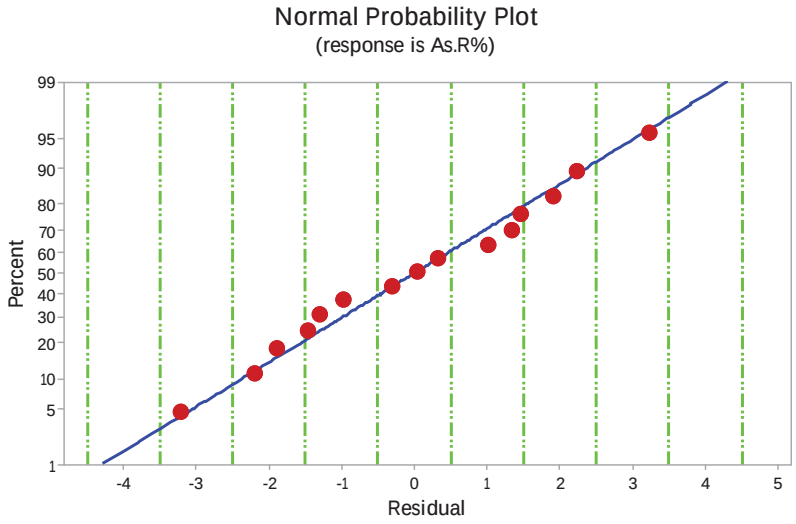
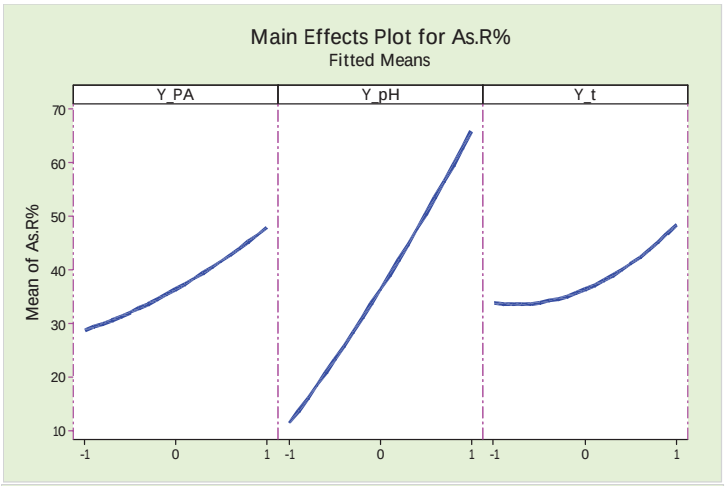


Fig. 1: Normplot of standardized residuals for As(III) removal

(a)



(b)

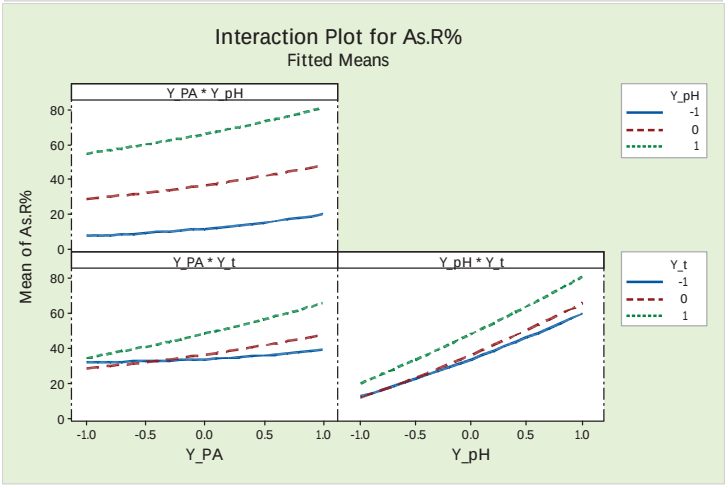


Fig. 2: The mean effects diagram (a) and 2-way interaction plot (b) of studied factors affected on As(III) uptake

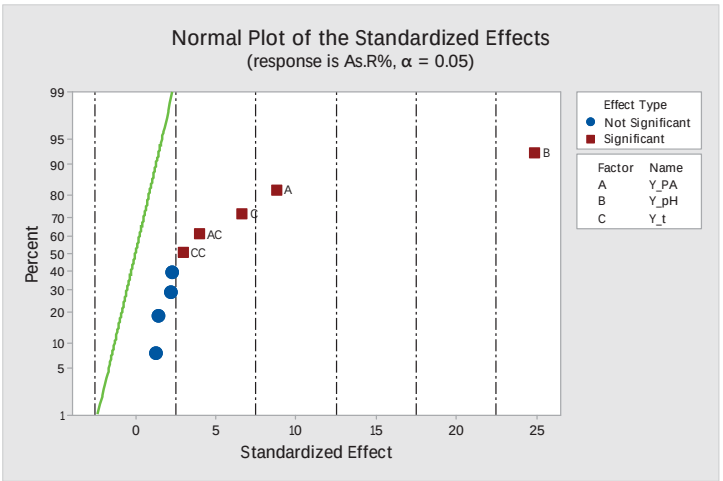


Fig. 3: Normplot of the standardized effects for As(III) uptake by PJB

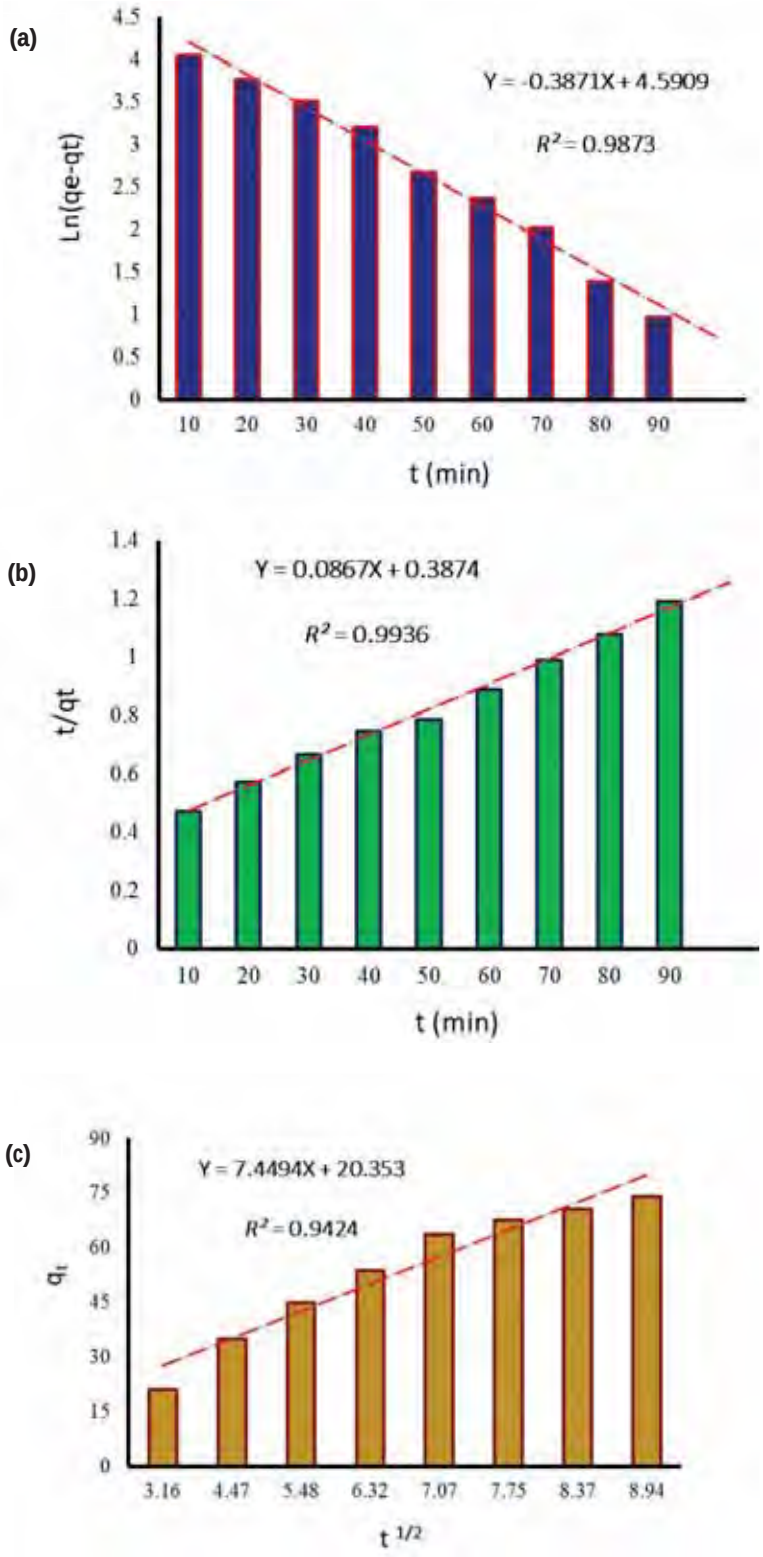


Fig. 4: Kinetics curves of a) P-F-O, b) P-S-O, and c) I-D-M related to the As(III) biosorption by PJB

Table 4. The constant parameters associated with P-F-O, P-S-O, and I-D-M.

Models	P-F-O			P-S-O			I-D-M		
	q_e	k_1	R^2	q_e	k_2	R^2	k_p	C	R^2
	98.58	0.0387	0.987	114.94	1.95×10^{-4}	0.994	9.39	-6.667	0.986

coefficient (R^2_{pred}) value of 0.9053 was in reasonable agreement with the adjusted coefficient (R^2_{adj}) of 0.9820. The analysis showed a positive agreement between the experimental values and the predicted values that corresponded to them.

The main effects and interactions of the variables affecting As(III) removal values, as determined by the BBD model, are depicted in the graphical representation illustrated in Fig. 2. As(III) uptake was evidently enhanced at higher levels of all factors, with a more significant increasing trend noted in the Y_pH factor in relation to the removal percentage. This trend was also corroborated by the interaction effects of the variables.

The standardized effects linked to the removal of As(III) are depicted in Fig. 3. The coded factors B, A, C, AC, and CC (Y_{pH} , Y_{PA} , Y_t , $Y_{PA}.Y_t$, and Y_t^2), respectively are positioned further from the hypothetical italic line, thereby underscoring the significance of these factors. The analysis results validate the data acquired through the regression equation. The results presented in Table 3 of the BBD indicate that the p-value for the *lack-of-fit* term was not significant (0.132), affirming the model's validity. According to the optimization result for As(III) removal by PJB, maximum metalloid uptake was 92.6%, achieved at maximum operational factor levels (PA = 8:1, pH of synthetic wastewater = 7.5, and contact time = 90 min). The validation results determined that PJB efficiency in As(III) removal from the synthetic solution was 91.11%. The narrow gap between the predicted values generated by the model and the actual measurements reinforces the model's credibility and high level of accuracy.

Kinetics of As(III) biosorption

The study of kinetics in adsorption processes plays a key role in evaluating the performance of adsorbents and in understanding the mechanisms that govern these interactions (Qiu *et al*., 2009; Samimi and Moeini, 2020). Adsorption is widely used for environmental remediation, including the removal of dyes, heavy metals, and other hazardous substances from aqueous solutions (Dubey and Rao, 2012; Lou, 2017; Safari *et al*., 2019; Samimi and Shahriari-Moghadam, 2023). Comprehending adsorption kinetics is fundamental for determining the suitability of adsorbents in the treatment of wastewater and air, highlighting its importance as a key area of study in environmental remediation (Kajjumba *et al*., 2018). The evaluation of the sorption rate of As(III) by PJB over time was conducted primarily through the application of adsorption kinetics, employing both the pseudo-first-order (P-F-O) and pseudo-second-order (P-S-O) kinetic models, along with the intraparticle diffusion mechanism (I-D-M). The linear representations of these models are delineated in Eqs. 6, 7, and 8. (Azimi *et al*., 2019; Samimi and Amiri, 2024).

$$\ln\left(q_e - q_t\right) = \ln q_e - k_1 t \tag{6}$$

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \tag{7}$$

$$q_t = k_p t^{\frac{1}{2}} + C \tag{8}$$

Where,

Parameter of k_2 (g/(mg.min)): adsorption rate constants for P-S-O

Parameter of k_1 (1/min): adsorption rate constants for P-F-O

Parameter of k_p (mg/(g.min$^{1/2}$): I-D-M constant

The kinetics study was performed with all runs maintained at a pH level of 7.5. Figs. 4a-c illustrate the kinetics graphs for P-F-O, P-S-O, and I-D-M in relation to the biosorption of As(III).

P-F-O kinetics having a higher R^2 than P-S-O kinetics does not necessarily indicate the true adsorption mechanism (Vareda, 2023). According to the summary in Table 4, the P-S-O kinetics demonstrate a superior R2 value of 0.994 when compared to P-F-O's 0.987 and I-D-M's 0.986. This finding implies that the chemical interaction between the functional groups of PJB and As(III) is the key rate-limiting step in the adsorption process of the metalloid (Samimi and Shahriari-Moghadam, 2021).

CONCLUSION

Industrial wastewater containing heavy metals and metalloids presents serious environmental and health risks, attributed to their toxic properties, durability in the environment, and potential for bioaccumulation in biological systems. These contaminants can negatively impact plant growth, crop yields, and food safety when absorbed by farmlands. Arsenic is classified as a metalloid and can be found in both inorganic and organic forms, with the inorganic variants typically exhibiting higher toxicity. Arsenic contamination in wastewater is a significant environmental concern, particularly in effluents from metallurgical and chemical industries. It is imperative to treat wastewater with arsenic, as it poses a substantial threat to human health, the integrity of ecosystems, and agricultural productivity. Arsenic contamination affects millions of people worldwide, causing various health issues including skin cancers and internal carcinomas. While conventional methods like reverse osmosis and ion exchange are effective in treatment, they come with high costs and result in the production of sludge. The use of biomass-derived adsorbents is increasingly seen as a viable, environmentally sustainable, and cost-efficient method for addressing water pollution. In the current research, biomass obtained from the fruit of *Prosopis juliflora* was assessed for its ability to adsorb As(III) from synthetic wastewater. The findings indicated that all chosen experimental parameters, including the PJB-to-As(III) ratio, the pH of the synthetic wastewater, and the residence time, had a significant impact on the uptake of As(III) by PJB. This study aimed to examine the parameters and perform numerical optimization of the quadratic model to establish the ideal conditions for maximizing As(III) biosorption by PJB. The results of the statistical analysis indicated that the BBD model is highly accurate in predicting the optimal conditions for the adsorption of As(III) by PJB. Results from the optimization study on the elimination of As(III) from synthetic solutions via PJB demonstrate that the maximum uptake of the metalloid reached 92.6%, which was observed at the highest levels of the selected operational parameters. The sorption of As(III) adhered to a P-S-O model (R^2= 0.994), indicating that the primary factor limiting the uptake of the analyte was the chemical interaction between the functional groups present in PJB and the metalloid ions. The biomass obtained from the non-edible parts of Prosopis juliflora showed significant effectiveness in removing As(III) removal from aquatic ecosystems.

AUTHOR CONTRIBUTIONS

The corresponding author, M. Samimi, managed the project, supervised various stages of the study, wrote the original draft, and carried out the analysis and validation experiments. J. Nouri reviewed and edited the manuscript.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support of Kermanshah University of Technology for the current study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit:

http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims with regard to published maps and institutional affiliations.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
µm	Micrometre
ANOVA	Analysis of variance
BBD	*Box-Behnken* Design
C_0	Initial arsenic concentrations
As(III)	Arsenite
As(V)	Arsenate
$Na_2HAsO_3 \cdot 5H_2O$	Sodium arsenite salt
C_e	Final As(III) concentrations
As.R	As(III) removal
C_t	As(III) concentrations at time t
DOE	Design of experiments
Eq.	Equation
Fig.	Figure
g	Gram
I-D-M	Intraparticle diffusion mechanism
L	Liter
mg	Milligram
mg/g	Milligram per gram
mg/L	Milligram per liter
mL	Milliliter
min	Minute
No.	Number
PA	PJB-to-arsenic ratio
P-F-O	pseudo-first-order
PJB	*Prosopis juliflora* fruit biomass
pH	Potential of hydrogen
P-S-O	pseudo-second-order
q_e	Biosorption capacity (at equilibrium)
q_t	Biosorption capacity (at time t)
R^2	Coefficient of determination
R^2_{adj}	Adjusted R^2
R^2_{pred}	Predicted R^2
rpm	Revolutions per minute
RSM	Response surface methodology
V	Volume
Y_{PA}	PJB-to-arsenic ratio - Coded factor
Y_{pH}	pH value - Coded factor
Y_t	Contact time - Coded factor
a_0	Offset term
a_i	Linear term
a_{ii}	Quadratic term
a_{ij}	Interaction term

REFERENCES

Abdallat, R.; Bdour, A.; Abu Haifa, A.; Al Rawash, F.; Almakhadmah, L.; Hazaimeh, S., (2024). Development of a sustainable, green, and solar-powered filtration system for E. coli removal and greywater treatment. Global J. Environ. Sci. Manage., 10(2): 435-450 (**16 pages**).

Abubakar, A.; Yusuf, H.; Syukri, M.; Nasution, R.; Yusuf, M.; Idroes, R., (2023). Heavy metals contamination in geothermal medicinal plant. Global J. Environ. Sci. Manage., 9(4): 995-1004 (**10 pages**).

Aghajani, M.J.; Ghani, M.; Raoof, J.B., (2024). Synthesis of MOF-5 modified Bi2WO6 polyoxometalate accommodated on the pores of hollow fiber for HF-SPME of acetamiprid, abamectin and diazinon and their determination by high performance liquid chromatography-ultraviolet. Chem. Methodol., 8(4): 279-292 (**14 pages**).

Al-Azzawi, M.A.; Saleh, W.R., (2023). Fabrication of Environmental Monitoring Amperometric Biosensor Based on Alkaloids Compound Derived from Catharanthus Roseus Extract Nanoparticles for Detection of Cadmium Pollution of Water. Chem. Methodol., 7(5): 358-371 (**14 pages**).

Asadullah, M.; Ain, Q.u.; Ahmad, F., (2022). Investigation of a Low Cost, Stable and Efficient Adsorbent for the Fast Uptake of Cd (II) from Aqueous Media. Adv. J. Chem. A., 5(4): 345-356 (**12 pages**).

Azimi, N.; Azimi, P.; Samimi, M.; Mansouri Jalilian, T., (2019). Ultrasonic-assisted adsorption of Ni (II) ions from aqueous solution onto Fe_3O_4 nanoparticles. Adv. Nanochem., 1(2): 66-72 (**7 pages**).

Bakar, B. A.; Idawanni, I.; Azis, A.; Kurniawati, S.; Giamerti, Y.; Yardha, Y.; Purba, R.; Abdullah, S.; Jonharnas, J.; Mustikawati, D.R., (2024). Bibliometric analysis of biochar application for environmental management in agricultural sector. Global J. Environ. Sci. Manage., 10(SI): 237-250 (**14 pages**).

Balasubramanian, N.; Madhavan, K., (2001). Arsenic removal from industrial effluent through electrocoagulation. Chem. Eng. Technol., 24(5): 519-521 (**3 pages**).

Cheraghipoor, M., Zakeri, M.; Moghadam, H.; Samimi, M., (2024). A Feasibility Study for the Preparation of Green Copper-Colored Mica Pearlescent Pigments. Adv. J. Chem. A, 7(3): 338-346 (**9 pages**).

Douglas, I., (2018). The challenge of urban poverty for the use of green infrastructure on floodplains and wetlands to reduce flood impacts in intertropical Africa. Landsc. Urban Plan., 180: 262-272 (**11 pages**).

Dubey, S.S.; Rao, B.S., (2012). Kinetic models in adsorption-a review. Asian J. Res. Chem., 5(1): 8-13 (**6 pages**).

Ebrahimzadeh, P.; Maleki, B.; Ghani, M.; Peiman, S., (2024). High-performance Fe3O4@ SiO2@ Mel@ DABCO catalyst for synthesis of chromene derivatives and solid phase microextraction of fipronil and prometryn in food samples followed by HPLC-UV determination. Chem. Methodol., 8(11): 833-855 (**23 pages**).

Ehzari, H.; Safari, M.; Samimi, M.; Shamsipur, M.; Gholivand, M.B, (2022). A highly sensitive electrochemical biosensor for chlorpyrifos pesticide detection using the adsorbent nanomatrix contain the human serum albumin and the Pd: CdTe quantum dots. Microchem. J., 179: 107424 (**10 pages**).

Elhadeuf, K.; Bougdah, N.; Balaska, F.; Chikhi M., (2023). Experimental Study and Modeling by the Complete Factorial Plan of the Elimination of Textile Dye by Electrocoagulation Using Aluminum from Recycled Cans. Chem. Methodol., 7(3): 183-199 (**17 pages**).

Erdag, E.; Kucuk, M.; Aksoy, U.; Abacioglu, N.; Ozer Sehirli, A., (2023). Docking Study of Ligands Targeting NLRP3 Inflammatory Pathway for Endodontic Diseases. Chem. Methodol., 7(3): 200-210 (**11 pages**).

Eshetu, A.A.; Asegie, A.M.; Addisalem, S.T.; Hailu, F.; Tamerat, T., (2024). Beyond eradication: Unveiling local voices and proactive management strategies for Prosopis juliflora in eastern Ethiopia's arid landscape. Scientific African, 26: e02462 (**15 pages**).

Fatima, N.; Waheed, H.; Raza, A.; Mukhtar, A.; Ahmad, F., (2024). A Critical Review on Membrane Technology and Its Application in CO2 Capturing. Chem. Methodol., 8(9): 662-698 (**38 pages**).

Gebrehiwot, K.; Steger, C. (2024). A Systematic Review of Prosopis juliflora (Sw.) DC. Research in Ethiopia Reveals Gaps and Opportunities for Advancing Management Solutions. Environ. Sustain. Indic., 100506 (**12 pages**).

Goudarziafshar, H.; Zafari, M.; Moosavi-Zare, A.A.R., (2024). Catalytic application of porous carbon/Fe_3O_4 nanocomposite on the synthesis of pyranopyrazole derivatives. Chem. Methodol, 8(11): 820-832 (**13 pages**).

Handayani, T.; Djarot, I.N.; Widyastuti, N.; Arianti, F.D.; Pertiwi, M.D.; Rifai, A.; .; Sitomurni, A.I.; Nur M.M.A.; Parminto, A. K.; Nurmala Dewi, R.; Nuha, N.; Hariyanti, J.; Pinardi, D.; Suryana, Y.; Aziz, A.; Rochmadi, T.; Syamsudin, E.; Lomak P.A.; Hadi, A.; Yuniastuti, E.; Putri, N.A., (2024). Biogas quality and nutrient remediation in palm oil mill effluent through chlorella vulgaris cultivation using a photobioreactor. Global J. Environ. Sci. Manage., 10(4): 1519-1542 (**24 pages**).

Hawrami, K.A.; Baset, A.K., (2024). Trace element concentrations, spatial distribution patterns, and risk potential in soils from urban and peri urban agriculture. Global J. Environ. Sci. Manage., 10(4): 2045-2066 (**22 pages**).

Hammond, C.M.; Root, R.A.; Maier, R.M.; Chorover, J., (2018). Mechanisms of arsenic sequestration by Prosopis juliflora during the phytostabilization of metalliferous mine tailings. Environ. Sci. Technol, 52(3): 1156-1164 (**9 pages**).

Kajjumba, G.W.; Emik, S.; Öngen, A.; Özcan, H.K.; Aydın, S., (2018). Modelling of adsorption kinetic processes—errors, theory and application. Advanced sorption process applications, 1-19 **(19 pages).**

Kamaraj, M.; Kamali, P.; Kaviya, R.; Abishek, K.; Navinkumar, B.; Nithya, T.G.; Aravind, J., (2024). Human hair biochar to remove malachite green dye and bisphenol-A contamination. Global J. Environ. Sci. Manage., 10(3): 1005-1016 (**12 pages**).

Qiu, H.; Lv, L.; Pan, B.C.; Zhang, Q.J.; Zhang, W.M.; Zhang, Q.X., (2009). Critical review in adsorption kinetic models. J. Zhejiang Univ. Sci., 10(5): 716-724 (**9 pages**).

Lou, S., (2017). Applied adsorption kinetics model for removal of hazards from aqueous solution: more informational parameters for industrial design. Journal of Environmental Science and Public Health, 1(4): 228-239 (**12 pages**).

Luo, T.; Cui, J.; Hu, S.; Huang, Y.; Jing, C., (2010). Arsenic removal and recovery from copper smelting wastewater using TiO2. Environ. Sci. Technol., 44(23): 9094-9098 (**5 pages**).

Mehari, Z.H., (2015). The invasion of Prosopis juliflora and Afar pastoral livelihoods in the Middle Awash area of Ethiopia. Ecological Processes, 4: 1-9 (**9 pages**).

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination. 542: 116092 (**8 pages**).

Mohadesi, M.; Gouran, A.; Darabi, F.; Samimi, M., (2024a). Sunflower seed pulp ash as an efficient and eco-friendly adsorbent for Congo red uptake: characteristics, kinetics, and optimization. Water Pract. Technol., 19(1): 228-240 (**12 pages**).

Mohadesi, M.; Samimi, M.; Chahardoli, F.; Kasaie, M.R.; Gouran, A., (2024b). Simultaneous removal of Pb (II) and Cr (VI) from a steel company wastewater using various green adsorbents: Material characterization and numerical optimization. Water Pract. Technol., 19(11): 4473-4485 (**13 pages**).

Nicomel, N.R.; Leus, K.; Folens, K.; Van Der Voort, P.; Du Laing, G., (2016). Technologies for arsenic removal from water: current status and future perspectives. Int. J. Environ. Res. Public Health, 13(1): 62 (**24 pages**).

Oliver Paul Nayagam, J.; Prasanna, K., (2023). Response surface methodology and adaptive neuro-fuzzy inference system for adsorption of reactive orange 16 by hydrochar. Global J. Environ. Sci. Manage, 9(3): 373-388 (**16 pages**).

Osipova, E.S.; Gladkov, E.A., (2024). Heracleum Sosnowskyi Manden. as a Source of Valuable Chemicals (Elimination with Utility). Chem. Methodol., 8(12): 944-956 (**13 pages**).

Phewnil, O.; Pattamapitoon, T.; Semwimol, N.; Wararam, W.; Duangmal, K.; Intaraksa, A.; Chunkao, K.; Maskulrath, P; Hanthayung, S.; Wichittrakarn, P., (2024). Effects of landslide hazards on quality of stream water and sediments. Global J. Environ. Sci. Manage., 10(3): 1099-1116 (**18 pages**).

Rembold, F.; Leonardi, U.; Ng, W.T.; Gadain, H.; Meroni, M.; Atzberger, C., (2015). Mapping areas invaded by Prosopis juliflora in Somaliland on Landsat 8 imagery. In Remote Sensing for Agriculture, Ecosystems, and Hydrology XVII, SPIE. 9637: 295-306 (**12 pages**).

Sabilillah, A.M.; Palupi, F.R.; Adji, B.K.; Nugroho, A.P., (2023). Health risk assessment and microplastic pollution in streams through accumulation and interaction of heavy metals. Global J. Environ. Sci. Manage., 9(4): 719-740 (**22 pages**).

Safari, M.; Moghadam, M.S.; Samimi, M.; Azizi, Z., (2019). Study of the Optimal Conditions for Zn+2 Removal Using the Biomass of Isolated Bacteria from Ravang Mine. Iran. J. Soil Water Res., 50(1): 149-160 (**12 pages**).

Samimi, M., (2024). Efficient biosorption of cadmium by *Eucalyptus globulus* fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 (**12 pages**).

Samimi, M.; Amiri, K., (2024). Zinc alginate beads as an effective biosorbent for the removal of Eosin-B from aquatic solutions: Equilibrium, kinetics, and thermodynamic behaviors. Chem. Methodol., 8(5): 351-363 (**13 pages**).

Samimi, M.; Moeini, S., (2020). Optimization of the Ba+ 2 uptake in the formation process of hydrogels using central composite design: Kinetics and thermodynamic studies of malachite green removal by Ba-alginate particles. J. Part. Sci. Technol., 6(2): 95-102 (**8 pages**).

Samimi, M.; Validov, S., (2018). Characteristics of pDNA-loaded chitosan/alginate-dextran sulfate nanoparticles with high transfection efficiency. Rom. Biotech. Lett. 23(5): 13996-14006 (**11 pages**).

Samimi, M.; Moghadam, H., (2024a). Modified evacuated tube collector basin solar still for optimal desalination of reverse

osmosis concentrate. Energy. 289: 129983 (**8 pages**).
Samimi, M.; Moghadam, H., (2024b). Investigation of structural parameters for inclined weir-type solar stills, Renew. Sustainable Energy Rev., 190: 113969 (**10 pages**).
Samimi, M.; Mansouri, E., (2024). Efficiency evaluation of Falcaria vulgaris biomass in Co(II) uptake from aquatic environments: characteristics, kinetics and optimization of operational variables. Int. J. Phytoremed., 26(4): 493-503 (**11 pages**).
Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 (**10 pages**).
Samimi, M.; Safari, M., (2022). TMU-24 (Zn-based MOF) as an advance and recyclable adsorbent for the efficient removal of eosin B: Characterization, equilibrium, and thermodynamic studies. Environ. Prog. Sustain. Energy, 41(5): e13859 (**9 pages**).
Samimi, M.; Shahriari Moghadam, M., (2018). Optimal conditions for the biological removal of ammonia from wastewater of a petrochemical plant using the response surface methodology. Global J. Environ. Sci. Manage., 4(3): 315-324 (**10 pages**).
Samimi, M.; Shahriari Moghadam, M., (2020). Phenol biodegradation by bacterial strain O-CH1 isolated from seashore. Global J. Environ. Sci. Manage., 6(1): 109-118 (**10 pages**).
Samimi, M.; Shahriari-Moghadam, M., (2021). Isolation and identification of *Delftia lacustris* Strain-*MS3* as a novel and efficient adsorbent for lead biosorption: Kinetics and thermodynamic studies, optimization of operating variables. Biochem. Eng. J., 173: 108091 (**9 pages**).
Samimi, M.; Shahriari-Moghadam, M., (2023). The *Lantana camara* L. stem biomass as an inexpensive and efficient biosorbent for the adsorptive removal of malachite green from aquatic environments: kinetics, equilibrium and thermodynamic studies. Int. J. Phytoremed., 25(10): 1328-1336 (**9 pages**).
Samimi, M.; Shahriari-Moghadam, M., (2024). Bioaccumulation efficiency comparison of heavy metals in Verbascum speciosum, Acantholimon hohenackeri, Acanthophyllum microcephalum, and Euphorbia macroclada, grown around lead and zinc mines. Iranian Journal of Research in Environmental Health, 9(4): 349-360 (**12 pages**).
Samimi, M.; Shahriari Moghadam, M., (2025). Efficient biodegradation of crude oil by novel *Pseudomonas aeruginosa* strain isolated from petrochemical wastewater: identification and optimization. Pet. Sci. Technol., 43: 1-18 (**18 pages**).
Samimi, M.; Zakeri, M.; Alobaid, F.; Aghel, B., (2023a). A Brief Review of Recent Results in Arsenic Adsorption Process from Aquatic Environments by Metal-Organic Frameworks: Classification Based on Kinetics, Isotherms and Thermodynamics Behaviors. Nanomater., 13(1): 60 (**12 pages**).
Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023b). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremed., 25(12): 1636-1642 (**7 pages**).
Sulistyowati, L.; Yolanda, Y.; Andareswari, N., (2023). Harbor water pollution by heavy metal concentrations in sediments. Global J. Environ. Sci. Manage., 9(4): 885-898 (**14 pages**).
Vahabisani, A.; An, C., (2021). Use of biomass-derived adsorbents for the removal of petroleum pollutants from water: a mini-review. Environ. Syst. Res., 10(1): 25 (**10 pages**).
Vareda, J.P., (2023). On validity, physical meaning, mechanism insights and regression of adsorption kinetic models. J. Mol. Liq., 376: 121416 (**14 pages**).
Yadav, N.; Rana, A.C., (2020). Pharmacological and pharmacognostical aspect of Prosopis juliflora: A review. World journal of advanced research and reviews, 8(1): 036-052 (**17 pages**).
Younas, M.; Bacha, A.U.R.; Khan, K.; Nabi, I.; Ullah, Z.; Humayun, M.; Hou, J., (2024). Application of manganese oxide-based materials for arsenic removal: A review. Sci. Total Environ., 170269.
Zodi, S.; Potier, O.; Michon, C.; Poirot, H.; Valentin, G.; Leclerc, J.P.; Lapicque, F., (2011). Removal of arsenic and COD from industrial wastewaters by electrocoagulation. J. Electrochem. Sci. Eng., 1(1): 55-65 (**11 pages**).

AUTHOR (S) BIOSKETCHES

Samimi, M., Ph.D., Associate Professor, Department of Chemical Engineering, Faculty of Engineering, Kermanshah University of Technology, Kermanshah, Iran.
- Email: *m.samimi@kut.ac.ir*
- ORCID: 0000-0003-3098-7283
- Web of Science Researcher ID: AAT-2290-2021
- Scopus Author ID: 24478806000
- Homepage: http://research.kut.ac.ir/~msamimi/en/

Nouri, J., Ph.D., Professor, 1Department of Environmental Health Engineering, Tehran University of Medical Sciences, Tehran, Iran. 21137 Spectrum, Irvine, Orange County 92618 USA.
- Email: *nourijafar@gmail.com*
- ORCID: 0000-0002-9982-3546
- Web of Science Researcher ID: B-2614-2008
- Scopus Author ID: 22951700700
- Homepage: http://old.tums.ac.ir/faculties/jnouri

HOW TO CITE THIS ARTICLE

Samimi, M.; Nouri, J., (2025). Optimized removal of trivalent arsenic from aquatic environments using Prosopis juliflora seed biomass. Global J. Environ. Sci. Manage., 11(2): 391-402.

DOI: 10.22034/gjesm.2025.02.02

URL: https://www.gjesm.net/article_721353.html

Global J. Environ. Sci. Manage. 11(2): 403-426, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Projection of future temperature variations in river basins under climate change scenarios using general circulation models

H. Hroub[1], M. Rahbeh[1,*], M.M. Zoubi[2], Q.Y. Abu-Afifeh[1], H. Al-Jawaldeh[1], N. Obeidat[1]

[1] *Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan*

[2] *Department of Chemistry, The University of Jordan, Amman 11942, Jordan*

ARTICLE INFO

Article History:
Received 23 August 2024
Revised 27 November 2024
Accepted 31 December 2024

Keywords:
Climate change impacts
General circulation models
Shared socioeconomic pathways
Statistical downscaling model
Temperature variations
Water resources

ABSTRACT

BACKGROUND AND OBJECTIVES: Jordan faces water resource challenges due to its arid climate and high population density. This study selects general circulation models for the Zarqa River Basin to project future temperature variations under the Shared Socioeconomic Pathways 2-4.5 and 5-8.5 scenarios across four periods: 2015-2040, 2041-2060, 2061-2080, and 2081-2100, assessing climate change impacts on water resources.

METHODS: The statistical downscaling model facilitated the projection of temperature fluctuations for the two Shared Socioeconomic Pathways throughout the four distinct timeframes. The model's predictors were derived from general circulation models and reanalysis datasets. Results showed a strong correlation between temperatures in the Zarqa River Basin and the selected general circulation models. During both the calibration period (1983-2000) and the validation period (2001-2014), the model accurately mirrored temperature characteristics. Projections were made for six stations within the Zarqa River Basin.

FINDINGS: Among the selected general circulation models, United Kingdm Earth System Modelling project and Hadley Centre Global Environmental Model 3—Global Coupled configuration 3.1 predicted the most rapid temperature increases. High-emission scenarios (Shared Socioeconomic Pathway 5-8.5) forecast larger temperature rises than low-emission scenarios (Shared socioeconomic pathway 2-4.5). Projections indicate that the northern part of the Zarqa River Basin will undergo more substantial warming than the southern section, with significant increases anticipated by the 2090s relative to the 2050s. Minimum temperatures are increasing at twice the rate of maximum temperatures. By 2100, maximum temperatures in the Shared Socioeconomic Pathway 2-4.5 scenario are expected to rise by 3.44-4.91 degrees Celsius, while in the Shared Socioeconomic Pathway 5-8.5 scenario, increases will range from 5.5-6.2 degrees Celsius.

CONCLUSION: The study successfully developed a Statistical Downscaling Model for future temperature projections in the Zarqa River Basin under the Shared Socioeconomic Pathway scenarios. The analysis reveals that the Zarqa River Basin is projected to undergo a climate characterized by higher temperatures and reduced precipitation, with notable increases in temperature expected by the late twenty-first century. These findings may provide valuable insights for regional hydrological and environmental modeling, aiding in the assessment of ecosystem sustainability.

DOI: 10.22034/gjesm.2025.02.03

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES **74**

NUMBER OF FIGURES **9**

NUMBER OF TABLES **6**

*Corresponding Author:
Email: *m.rahbeh@ju.edu.jo*
Phone: +9627 7519 7474
ORCID: 0000-0003-1270-5035

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Climate change stands as one of the most critical global challenges of our time, influencing both environmental systems and socioeconomic structures (Fenta *et al.*, 2018). Its consequences involve elevated temperatures, shifts in precipitation patterns, extreme weather phenomena, and challenges to food stability (Farzaneh *et al.*, 2024). Many countries are already experiencing the effects of human-induced climate change, which is expected to persist. Immediate consequences include rising sea levels, droughts, floods, wildfires, and more erratic rainfall patterns (Clarke *et al.*, 2022). Natural events, including volcanic activity, can play a role in climate changes; however, human endeavors, especially following the Industrial Revolution, have significantly worsened these effects (Kloub *et al.*, 2023; Al-Afeshat *et al.*, 2025). Human-driven greenhouse gas emissions have intensified the greenhouse effect, leading to a rise in global temperatures. A previously noted cooling trend associated with atmospheric aerosol pollution has been observed; however, greenhouse gases tend to accumulate more gradually and have a longer atmospheric lifespan. (Huseynov *et al.*, 2024). Over the last century, global temperatures have steadily risen, with the most significant warming observed in recent decades. From 2011 to 2020, global surface temperatures increased by more than 1.1 degrees Celsius (°C) compared to 1850-1900 (IPCC, 2014), mainly due to human activity. This rise in temperature is speeding up the thawing of polar ice, resulting in elevated sea levels and a greater risk of droughts, wildfires, and tropical cyclones (Abbass *et al.*, 2022; Abu-Afifeh *et al.*, 2023). Higher temperatures lead to various economic challenges, including lower productivity levels, risks to food security, and an increase in mortality rates (Roy, 2024). Increased temperatures contribute to a rise in evaporation rates, leading to drier soils and intensifying drought situations (Hamed *et al.*, 2023). This trend is causing a global rise in aridity (Ullah *et al.*, 2022). Jordan, with its diverse climates, faces heightened risks of environmental hazards, including droughts, floods, heat waves, and rising temperatures (RCCC, 2022). This country features two significant ecological zones: the Jordan Valley and the semi-arid Badia region, which contribute to its heightened vulnerability to the impacts of change impacts (GCF, 2022). Global climate models are used to project future climate conditions, but their uncertainty, arising from differences in initial conditions and model parameters, necessitates careful evaluation of their applicability to specific regions (Arshad *et al.*, 2021). Although these models play a vital role, they are limited in their ability to represent regional attributes and hydrological processes effectively (El-Samra *et al.*, 2024). Statistical downscaling methods bridge this gap by linking broader predictors to local outcomes, aiding in more accurate regional projections (Choi *et al.*, 2021). For example, Ec-Earth3-Veg successfully reproduced historical temperature and precipitation data in China (Lu *et al.*, 2022), while other models performed better in different regions such as Egypt (Hamed *et al.*, 2021). The coupled model intercomparison project has been instrumental in progressing climate modeling and enriching our scientific insights into climate systems (Eyring *et al.*, 2016). Temperature and precipitation variations are critical for understanding climate change's impact on energy cycles, agriculture, and water resources (Shawky *et al.*, 2022), with projected temperature rises of 2-5°C by the end of the century (Pomee and Hertig, 2022). To improve global model projections and deepen our understanding of regional vulnerabilities, local-level "downscaling" is crucial (Xu *et al.*, 2019). This enhanced data is vital for analyzing the impacts of climate change and shaping effective informing adaptation strategies. The latest edition, the coupled model intercomparison project 6 (CMIP6), introduces the earth system model (ESM) and the atmosphere-ocean general circulation model (AOGCM) (Grose *et al.*, 2020). With improved spatial resolutions and more sophisticated structures, these models include extra Earth system elements like biogeochemical cycles and ice masses, indicating a notable advancement from prior versions (Su *et al.*, 2021; Schlund *et al.*, 2020). Zhao *et al.* (2021) note that CMIP6 utilizes a variety of socio-economic pathways (SSPs), with five distinct greenhouse gas emission scenarios. Research by Almazroui *et al.* (2020) projected temperature increases across South Asia, with average temperatures expected to rise by 1.2°C, 2.1°C, and 4.3°C by 2100 under the SSP126, SSP245, and SSP585 scenarios, respectively. In a comparison of precipitation projections for Northeastern Iran between Coupled Model Intercomparison Project 5 (CMIP5) and CMIP6, Zamani *et al.* (2020) found that CMIP6 models

outperformed CMIP5 in many locations and seasons. Several research studies have leveraged general circulation models (GCMs) to investigate climate patterns from the past to the present and into the future. Specifically, the CMIP5 and CMIP6 GCMs have been utilized to analyze the implications of climate change on both temperature and precipitation (Richter and Tokinaga, 2020; Lun *et al.*, 2021; Ngoma *et al.*, 2021; Xu *et al.*, 2021; Ghazi and Jeihouni, 2022; Jose and Dwarakish, 2022; Noël *et al.*, 2022). Salehie *et al.* (2023) examined the impact of climate change on the Amu Darya River basin using 19 CMIP6 GCMs, forecasting temperature increases of 1.3–4.9°C for Tmax and 1.3–5.5°C for Tmin, along with an increase in precipitation of 9.9–12.4 percent (%). According to the findings of Onyutha *et al*. (2021), Uganda is expected to experience higher precipitation levels across different SSP scenarios between 2021 to 2100. In the Amman-Zarqa Basin, Al-Hasani *et al.* (2023) projected temperature increases of 2°C to 4.5°C and precipitation reductions of 3.7 % to 20.7% under the RCP4.5 and RCP8.5 scenarios, while Al Saodi *et al.* (2023) found variations in precipitation across different sub-catchments. The findings of these studies underscore the necessity for extensive evaluations across the entire basin. There is substantial documentation regarding how temperature affects the melting of snow and glaciers and the resulting streamflow, particularly in elevated areas (IPCC, 2014). Latif *et al.* (2020) found that the temperature in the Himalayan region increased by 0.7°C during the last century, a rise notably higher than the global average. with global temperatures approach a rise of 1.5°C, high-altitude regions are forecasted to undergo a temperature increase of 2.1°C. This trend is frequently associated with rising greenhouse gas emissions, especially in areas located at higher latitudes zones (Kraaijenbrink *et al.*, 2017). While climate change projections carry inherent uncertainties, global climate models offer realistic scenarios that help identify vulnerabilities in hydrologic systems and sediment dynamics, with local-to-regional assessments being increasingly vital due to growing concerns about climate impacts (Samuels *et al.*, 2010). The application of statistical downscaling models (SDSM) has been prevalent in examining the impacts of climate variations. Meenu *et al.* (2013) used SDSM to assess the hydrological impacts of climate change on the Tungabhadra River, employing the Linear Regression-based SDSM 4.2 for downscaling daily temperatures and precipitation based on the Hadley Centre Coupled Model 3 (HadCM3) GCM. Having been calibrated and validated, this model projected future hydrological changes over three time frames: 2011–2040, 2041–2070, and 2071–2099. The regression-based method introduced by Wilby *et al*. (2002) has established itself as a global standard for statistical downscaling. Hassan *et al.* (2014) applied SDSM with stochastic weather generators to forecast future rainfall and temperature in Peninsular Malaysia, finding SDSM generally outperformed the Long Ashton Research Station Weather Generator (LARS-WG) model. Kundu *et al.* (2017) employed SDSM to estimate future rainfall in Betul, Hoshangabad, and Raisen, calibrating and validating the model. Thakor *et al.* (2024) conducted an analysis of changes in rainfall and temperature within the Vadodara district, utilizing data from the Canadian Earth System Model 2 (CanESM2) to project future conditions based on various carbon emission scenarios derived from GCMs. Their findings show an upward trend in rainfall and temperature across the 2021–2100 period, with the highest temperature rise occurring in July. The study by Rana *et al*. (2024) employed SDSM to assess projected changes in precipitation and temperature in northwest Bangladesh. The study concluded that climate change is likely to lead to a reduction in precipitation and a rise in temperatures, which will adversely affect water resources in the area. Kumar *et al.* (2024) employed SDSM to analyze temperature extremes in Gangetic Plain smart cities, predicting warmer conditions and extreme temperatures by the end of the century. Abdallah *et al.* (2021) applied SDSM to the Yarmouk Basin, using the CanESM2 GCM, and projected a decrease in precipitation by 9.5% to 12.9% and temperature increases of 0.9°C to 2.01°C, depending on the emission scenario. Alsalal *et al.* (2024) conducted an analysis of temperature and precipitation trends in the Mujib Basin using the CMIP6 framework. The findings indicated a temperature rise ranging from 1.4°C to 6.8°C, alongside a decrease in precipitation between 4.61% to 23.2%. Studies on Jordan's climate indicate that the rate of warming is higher for minimum temperatures compared to maximum temperatures, with regional variations in precipitation trends (Abdulla *et al.*, 2009; Freiwan *et al.*, 2008). This study

uniquely contributes to the growing body of climate research by applying SDSM and CMIP6 models to the Zarqa River Basin (ZRB), a vital and highly water-stressed region in Jordan. This study distinguishes itself from similar research by providing high-resolution temperature projections that are localized, rather than generalized across wider geographical regions. It specifically examines the unique climatic and hydrological challenges associated with the basin under the SSP2-4.5 and SSP5-8.5 scenarios. By analyzing both maximum and minimum temperature trends across multiple GCMs, the study offers a comprehensive evaluation of regional temperature dynamics. These findings fill a critical gap in the literature, providing actionable insights for climate adaptation and water resource management in arid and semi-arid regions. The the current study aims to analyze projected climatic alterations focusing on two main goals; 1) to evaluate the efficacy of five CMIP6 GCMs in accurately simulating historical maximum and minimum temperatures from 1983 to 2014, 2) to predict future temperature changes over four specific time frames: near-term (2015–2040), mid-term (2041-2060), late mid-term (2060-2080), and long-term (2081–2100) under the SSP2-4.5 and SSP5-8.5 scenarios. This study has been carried out in the ZRB of Jordan, a region particularly vulnerable to climate change. The study has been conducted for the period from 1983 to 2014 for historical data analysis, with future projections focusing on four time periods: near-term (2015–2040), mid-term (2041-2060), late mid-term (2060-2080), and long-term (2081–2100). The current study has been carried out in the Zarqa River Basin of Jordan in 2024.

MATERIALS AND METHODS

Study area

The ZRB spans approximately 4,120 square kilometers, extending from its northernmost point to its confluence near the King Talal Dam. As the most densely populated region in Jordan, it accommodates roughly 65% of the country's inhabitants and is responsible for over 85% of its industrial activities. The region's climate is classified as Mediterranean, with hot, arid summers and cool, rainy winters. Annual precipitation averages between 150 and 400 millimeters (mm) (Hyarat *et al.*, 2022). This basin experiences a semi-arid and eastern Mediterranean climate, which includes two short transitional periods in both the fall and spring. Winters are cold and humid, while summers are hot and dry. In the eastern arid desert, annual rainfall is below 100 mm, whereas the western, wooded highlands receive over 500 mm. The basin experiences a mean annual temperature of 17.3°C, characterized by winter averages of 8°C and summer highs nearing 25°C. Monthly temperature ranges in January and July are between 13.7–3.5°C and 34.7–18.8°C, respectively (Al Mahamid, 2005). Located in northern Jordan, the ZRB is positioned between latitudes 31.86 and 32.5° North (N) and longitudes 35.67 and 36.7° East (E) (Fig. 1 Alongside key urban centers such as Zarqa and Jerash, the basin features Amman, the capital, where around 65% of the population resides, 80% of the industrial activities are concentrated, and a considerable amount of agricultural production takes place (DOS, 2017). Due to its sources and water quality, the surface water resources of the Zarqa River are primarily used for livestock watering and irrigation, making it a crucial water resource for Jordan (Al-Hasani *et al.*, 2023; Obeidat *et al.*, 2024).

Data collection and evaluation of GCMs performance

In this study, three types of meteorological datasets were utilized: observed historical data, reanalysis data, and GCM data. The ZRB was covered by 38 meteorological stations, as depicted in Fig. 1. The historical meteorological data for the period 1983-2014 included daily maximum air temperature (Tmax) at 2 meters (m) and daily minimum air temperature (Tmin) at 2 m. These data were collected from six meteorological stations, which are listed in Table 1. To effectively evaluate climate model performance and analyze impacts, it is necessary to obtain meteorological data from the basin. Daily observed data for maximum and minimum temperatures were obtained from the Ministry of Water and Irrigation (MWI) for the period spanning 1983 to 2014. Six stations were identified for the purpose of recording temperature data. These strategically placed stations throughout the basin acted as reference points for evaluating the results of GCMs and measuring their precision. The details of the time series and station locations are provided in Table 1. The predictor variables were derived from the National Center for Environmental Prediction/Atmospheric Research (NCEP/NCAR) datasets, with local station data used as the predictand. Daily data for large-scale predictor

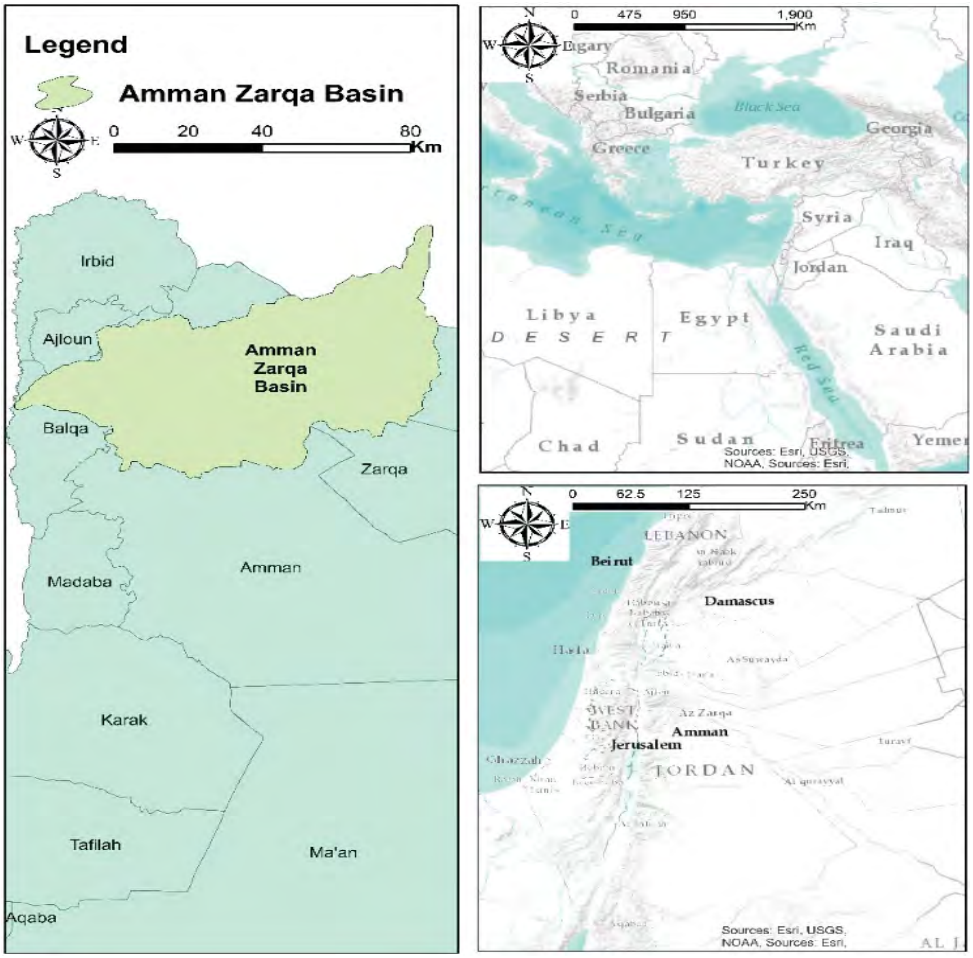


Fig. 1: Geographic location of the study area in the Zarqa River Basin in Jordan

Table 1: Basic meteorological station data used in this study

Station number	Station name	Period	Longitude	Latitude	Station number
AL0019	Amman Airport	1983-2014	35.98780109	31.97489014	AL0019
AL0035	K.H. Nursery Evaporation Station	1983-2014	35.84571316	32.08029341	AL0035
AL0053	King Talal Dam	1983-2014	35.83166217	32.19398593	AL0053
AL0057	Wadi Es-Sir	1983-2014	35.84696281	31.95584155	AL0057
AL0059	Um El-Jumal Evaporation Station	1983-2014	36.34414719	32.30221728	AL0059
AL0066	Khirebit Es Samra Evaporation Station	1983-2014	36.14565037	32.15146188	AL0066

variables, characterizing the contemporary climate conditions (1961–2005), were acquired. A total of five simulations from CMIP6 GCMs were collected, as presented in Table 2, and analyzed for their capacity to accurately reflect temperatures in the study area. The climate model data was sourced from the Earth Systems Grid Federation (ESGF) website (Eyring *et al.*, 2016). Historical data from the GCMs, covering the period from 1985 to 2014, were used, along with future projections based on the shared SSPs, specifically the medium forcing scenario SSP2-4.5 and the strong forcing scenario SSP5-8.5. The SSPs establish a framework for assessing potential future climate impacts and formulating strategies for both

Table 2: Basic information of the selected general circulation models

NO	GCMs	Institute and country of origin	Nominal resolution in kilometre (km)
1	ACCESS-CM2	Australian Community Climate and Earth System Simulator, Australia	250
2	HadGEM3-GC31-LL	The Hadley Centre Global Environmental Model 3—Global Coupled configuration 3.1	250
3	EC-Earth3-Veg	Earth Consortium Version 3 - Vegetation (EC-Earth3-Veg)/EC-Earth3-Veg-LR)	100
4	MRI-ESM2-0	Meteorological Research Institute, Japan	100
4	MRI-ESM2-0	Meteorological Research Institute, Japan	100
5	UKESM1-0-LL	UK Earth System Modelling project, UK	250

adaptation and mitigation (Feyissa *et al.*, 2023).

The GCMs are widely used to reconstruct historical climate trends and forecast future climatic conditions (Maraun *et al.*, 2010). Nonetheless, there are notable uncertainties in the regional use of GCMs, primarily stemming from inconsistencies between different models. These discrepancies include variations in resolution (either fine or coarse), the mechanisms driving climate responses (such as the influence of aerosols and the interactions among land, ocean, and atmospheric systems), as well as differences in temporal and spatial scales (Jain *et al.*, 2019). Conducting an in-depth evaluation of each selected GCM is vital to mitigate uncertainties linked to their utilization in specific regions. Typically, determining the accuracy of GCM simulations entails contrasting the results with reanalysis datasets or recorded climate records. A variety of indicators are employed by researchers in climate modeling to support this evaluation. The selection of meteorological stations was based on their geographic representation within the ZRB, availability of long-term, high-quality temperature records, and coverage of the baseline period (1983–2014). While these criteria facilitated effective calibration, inconsistencies in spatial distribution or localized influences may result in minor biases. Additionally, the resolution differences between GCMs (250 km) and the SDSM downscaling (100 km) impact the precision of future projections. By associating broad-scale predictors with recorded station data, the SDSM reduces these discrepancies and enhances the accuracy at a local level. Despite these efforts, residual uncertainties may persist due to the inherent limitations of coarse-resolution GCMs in capturing fine-scale climatic variations.

The statistical downscaling model

The SDSM, developed by Wilby, is a decision-support tool designed to assess the impact of local climate variations. Developed in Visual Basic, SDSM version 4.2 has found broad application in a variety of climate-focused research initiatives (Wilby *et al.*, 2002). This tool establishes statistical relationships between large-scale climate predictors and regional climatic variables, such as temperature, by employing multiple linear regression techniques. Should these established relationships continue to hold in future scenarios, they can facilitate the derivation of downscaled regional characteristics by incorporating interactions with predictors sourced from GCMs via a stochastic weather generator. Within every sub-model, there exist two unique progressions: the unconditional progression and the conditional progression. In the unconditional framework, temperature is generated directly without any transformation, demonstrating a linear relationship between the predictors and the predictand (for example, individual wind speeds can be used to derive regional airflow parameters). The SDSM encompasses five critical phases: the selection of variables, the calibration and validation of the model, the generation of weather data, and the projection of future climate scenarios (Zhang *et al.*, 2016). A crucial part of the statistical downscaling process involves screening variables between the predictand (such as maximum and minimum temperatures) and the predictor (large-scale atmospheric conditions). SDSM utilizes various tools, such as correlation matrices, partial correlations, P-values, histograms, and scatter plots, to help users identify the most effective predictors (Peng *et al.*, 2021). In this study, predictors were developed using the reanalysis datasets from NCEP/NCAR and CMIP6 GCMs to generate ensembles of current climate data within the SDSM framework. The standard predictors are normalized

Table 3: List of selected predictors in the ZRB

Station ID	Tmax	Tmin
AL0019	Shum, Temp, p500, P_z	Shum, Temp, r500, p8_z
AL0035	Shum, Temp, p500, r500	Shum, Temp, r500
AL0053	Shum, Temp, p500, p8_z	Shum, Temp, p8_z
AL0057	Shum, Temp, p500, r850	Shum, Temp, r500
AL0059	Shum, Temp, p850, p8_z	Shum, Temp, p8_z
AL0066	Shum, Temp, p850	Shum, Temp, r500

Table 4: List of the large-scale climate variables (predictors) used for downscaling

Predictor code	Description	Predictor code	Description
p500	500 hPa Geopotential height	p_th	1,000 hPa Wind direction
p8_v	850 hPa Meridional velocity	p5_f	500 hPa Wind speed
r500	500 hPa Specific humidity	p5_z	500 hPa Vorticity
Shum	1,000 hPa Specific humidity	p8_f	850 hPa Wind speed
p5_u	500 hPa Zonal velocity	p5zh	500 hPa Divergence
p_u	1,000 hPa Zonal velocity	p8_z	850 hPa Vorticity
p5_v	500 hPa Meridional velocity	p_f	1,000 hPa Wind speed
r850	850 hPa Specific humidity	temp	Screen (2 m) Air temperature
p_v	1,000 hPa Meridional velocity	p8zh	850 hPa Divergence
p8_u	850 hPa Zonal velocity	p__z	1,000 hPa Vorticity
mslp	Mean sea level pressure	p8th	850 hPa Wind direction
p850	850 hPa Geopotential height	p_zh	1,000 hPa Divergence
p5th	500 hPa Wind direction	prep	Precipitation

Note: HectoPascals (hPa)

and assembled into predictor datasets. For this analysis, the predictors include shum, Temp, p500, P_z, p8-z, r500, r850, and p8_z. Table 3 provides a list of the most appropriate predictors for the observed predictands at six meteorological stations throughout the ZRB, while Table 4 shows the correlation matrix between the predictand and the 26 NCEP predictors.

The model's effectiveness is largely determined by the choice of relevant predictors during the screening phase for predictands within the SDSM framework. Although various statistical and graphical tools, such as correlation matrices and P-values, can be utilized to identify the best predictors, it is vital to include robust statistical parameters in the evaluation process to mitigate uncertainties related to SDSM applications. To evaluate the model's predictive performance, the following metrics were employed; Nash–sutcliffe efficiency (NSE), coefficient of determination (R^2), root mean square error (RMSE), and bias correction (Pbias), using Eqs. 1 to 4 (Rathinasamy *et al.*, 2014). The NSE assesses the degree of correspondence between simulated and observed data, while R^2 quantifies the extent to which the model explains the observed variance. Optimal performance for both metrics occurs when their values are close to 1. RMSE quantifies the average error magnitude, with lower values indicating higher accuracy, and Pbias evaluates the model's tendency to overestimate or underestimate, with smaller absolute values signifying reduced bias. Future climate forecasts are largely contingent upon the past performance of climate models. In this study, HadGEM3-GC31-LL and UKESM1-0-LL demonstrated strong agreement with observed temperature data during the baseline period (1983–2014), reflected in high correlation coefficients, low error metrics (RMSE and MAE), and accurate simulation of seasonal and extreme temperature patterns. The impressive performance demonstrates that these models successfully reflect the physical mechanisms driving temperature changes in the ZRB. Consequently, their future projections under SSP2-4.5 and SSP5-8.5 scenarios are considered reliable for assessing climate change impacts in the region (Rathinasamy *et al.*, 2014).

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(X_{oi} - X_{mi}\right)^2}{\sum_{i=1}^{n}\left(X_{oi} - \bar{X}_{mi}\right)^2} \quad (1)$$

$$R^2 = \frac{\sum_{i=1}^{n}\left(X_{oi} - \bar{X}_{oi}\right)\left(X_{mi} - \bar{X}_{mi}\right)}{\sqrt{\left(\sum_{i=1}^{n}\left(X_{oi} - \bar{X}_{oi}\right)^2\right)\left(\sum_{i=1}^{n}\left(X_{mi} - \bar{X}_{mi}\right)^2\right)}} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{oi} - X_{mi}\right)^2}{n}} \quad (3)$$

$$P_{bias} = \frac{\sum_{i=1}^{n}\left(X_{mi} - X_{oi}\right)}{\sqrt{\sum_{i=1}^{n} X_{oi}}} \times 100 \quad (4)$$

Where, X_{oi} is the observed prediction for day iii, X_{mi} is the modeled outcome for day iii, $\bar{X}_{oi}$ is the average of measured values over the study period and n is the total number of observed data points. Collectively, these metrics deliver an extensive analysis of how well the model performs. High values of R^2 and NSE, combined with low RMSE and minimal Pbias, are indicative of an effective and reliable model. This diverse methodology provides a solid framework for validating the predictions of climate models (Rathinasamy *et al.*, 2014).

RESULTS AND DISCUSSION

Selection of GCMs

When evaluating GCMs, it is crucial to compare their outputs against observed historical data, as previous robust predictions may not guarantee reliable future projections without such validation (Knutti, 2008). The study focused on contrasting historical climatic data with modeled datasets from five different GCMs as part of the "historical" experiments conducted between 1983–2014. The results, illustrated through Taylor diagrams (Figs. 2 and 3), show monthly Tmax and Tmin correlations at six meteorological stations. The placement of GCM points on these diagrams, indicated by their distance from the green line, assists in identifying the most suitable GCMs for each station. GCMs demonstrating high correlations and minimal errors showed superior simulation accuracy relative to observed values. For Tmax (Fig. 2), EC-Earth3-Veg, ACCESS-CM2, HadGEM3-GC31-LL, UKESM1-0-LL, and MRI-ESM2-0 achieved strong correlation coefficients at Amman Airport, King Talal Dam, Um El-Jumal Evap. Station, and Khirebit Es Samra Evap. Station (0.981, 0.989, 0.978, 0.991, and 0.992, respectively). Micro climate 6 and MRI-ESM2-0 demonstrated the highest correlations at stations AL0019 and AL0057 (UKESM1-0-LL: 0.991; MRI-ESM2-0: 0.992) and AL0035 (HadGEM3-GC31-LL: 0.981; MRI-ESM2-0: 0.978). At AL0059, correlations for EC-Earth3-Veg, ACCESS-CM2, HadGEM3-GC31-LL, UKESM1-0-LL, and MRI-ESM2-0 were 0.982, 0.983, 0.985, 0.992, and 0.993, respectively, highlighting a strong agreement between modeled and observed data. For Tmin, MRI-ESM2-0 achieved the best correlations at AL0035 and AL0066, with coefficients of 0.992 and 0.994, respectively. Additionally, ACCESS-CM2 and MRI-ESM2-0 exhibited the highest Tmin correlation values at AL0035, both scoring 0.983. These findings underscore the robustness of certain GCMs, particularly MRI-ESM2-0, in accurately simulating both Tmax and Tmin across various stations.

At station AL0019, UKESM1-0-LL and MRI-ESM2-0 achieved correlation coefficients of 0.994 and 0.996, respectively, while at AL0066, these models demonstrated correlations of 0.988 and 0.991. For station AL0035, the correlation coefficients for Tmin were 0.953 for EC-Earth3-Veg, 0.962 for ACCESS-CM2, 0.975 for HadGEM3-GC31-LL, 0.989 for UKESM1-0-LL, and 0.991 for MRI-ESM2-0, indicating a strong agreement between the GCM outputs and observed data (Fig. 3). At station AL0059, ACCESS-CM2 and HadGEM3-GC31-LL exhibited the highest correlations with Tmin, achieving values of 0.976 and 0.985, respectively. Notably, UKESM1-0-LL and MRI-ESM2-0 demonstrated superior correlation coefficients of 0.992 and 0.993, respectively, for Tmin at AL0059. These outcomes emphasize the strength of MRI-ESM2-0 and UKESM1-0-LL in providing accurate simulations of Tmin for the stations under evaluation.

SDSM downscaling

The study designated 1983–2000 as the calibration phase and 2001–2014 as the validation phase. Table 5 summarizes the evaluation metrics—R^2, RMSE, NSE, and Pbias—across six meteorological stations for both maximum and minimum monthly air temperatures during these periods. During the simulation phase, both temperature variables exhibited R^2 and NSE values that consistently approached 1.000. For maximum air temperature, RMSE values ranged from 0.032 to 1.102 during calibration and from 0.103 to 0.964 during validation. The calibration phase exhibited RMSE values for minimum air temperature

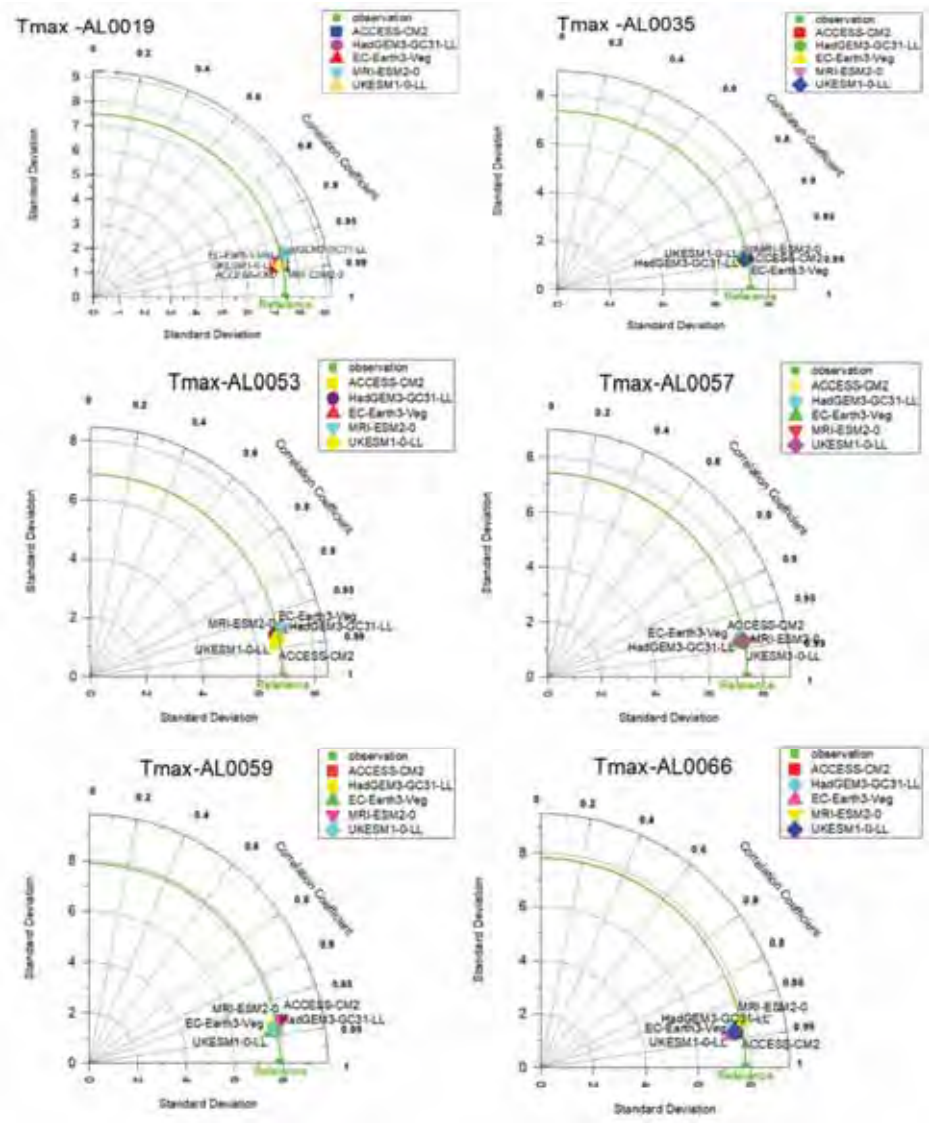


Fig. 2: Taylor diagrams of Tmax for each CMIP6 GCMs at each station

that varied from 0.035 to 0.105, whereas the validation phase showed values ranging from 0.192 to 0.320. The absolute Pbias values varied from 0.012% to 9.23% during the downscaling processes. These findings illustrate that the SDSM accurately reflects the fluctuations of maximum and minimum air temperatures in the study basin. The results of this study indicated that the validation phase was more effective than the calibration phase. The downscaling results demonstrated that predictors from the dataset effectively capture local-scale attributes. Overall, the SDSM proved highly effective in simulating climatic variables during both the calibration and validation phases within the ZRB.

Analysis of climatic variables at each station

Observed climatic variables from the historical period (1983–2014) were compared to projections from selected GCMs (ACCESS-CM2, HadGEM3-GC31-LL, EC-Earth3-Veg, MRI-ESM2-0, UKESM1-0-LL) under two SSP scenarios: SSP2-4.5 and SSP5-8.5. Under SSP5-8.5, the most severe warming is projected,

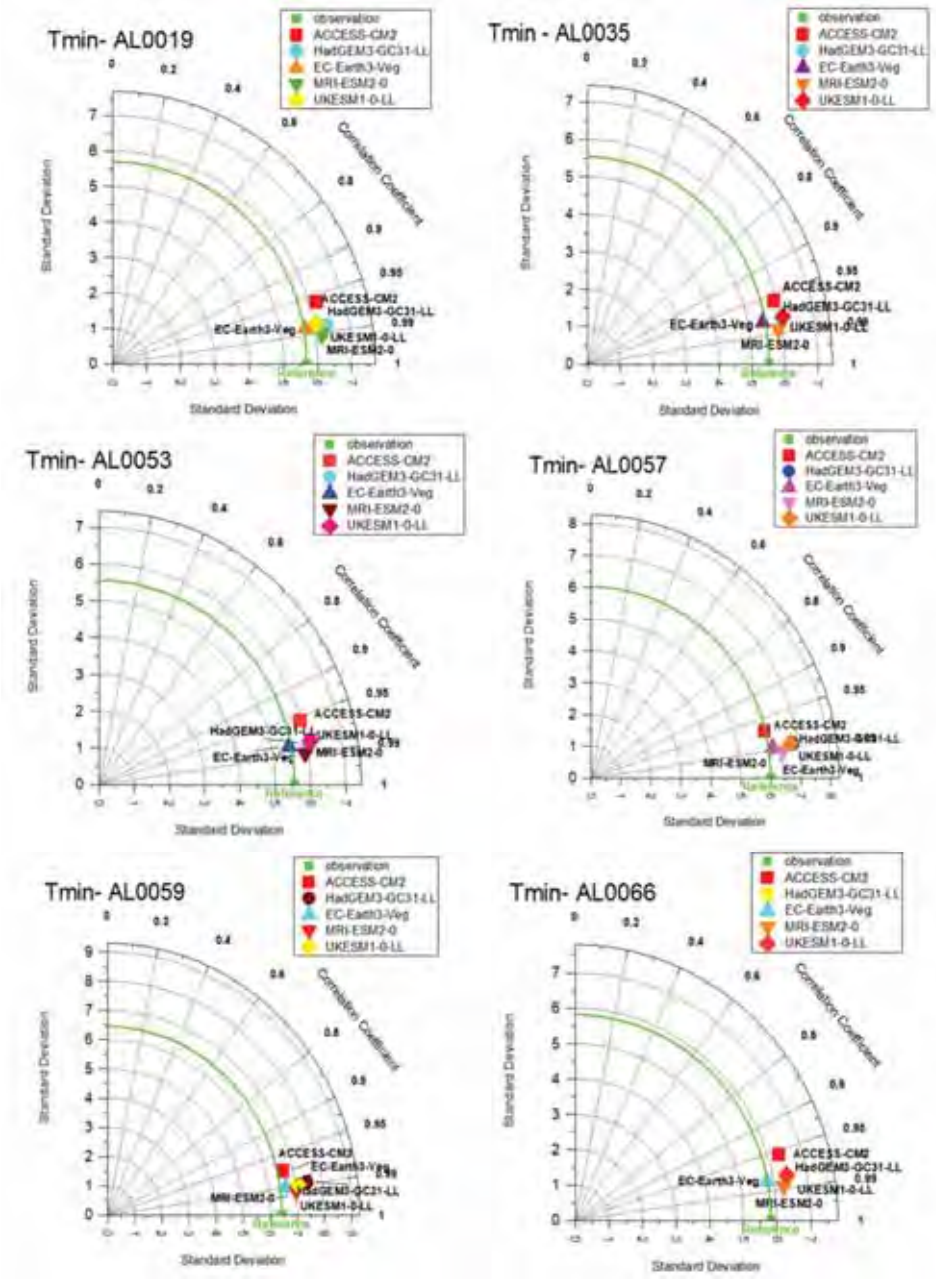


Fig. 3: Taylor diagrams of Tmin for each GCM at each station

while SSP2-4.5 represents a less intense warming scenario. Compared to the observed Tmax during the reference period, Tmax under SSP2-4.5 is projected to increase by 1.55°C, 1.49°C, 1.29°C, 0.68°C, and 1.65°C in 2061–2080 and by 1.87°C, 2.40°C, 2.10°C, 1.10°C, and 2.33°C in 2081–2100 for ACCESS-CM2, HadGEM3-GC31-LL, EC-Earth3-Veg, MRI-ESM2-0, and UKESM1-0-LL, respectively. Under SSP5-8.5, Tmax is expected to rise by 2.61°C, 3.13°C, 2.98°C, 2.35°C, and 3.13°C in 2061–2080, and by 4.12°C, 5.13°C, 4.90°C, 3.67°C, and 4.98°C in 2081–2100 for the same GCMs, relative to the reference period. The forecast indicates that Tmin will warm less significantly than Tmax at the six meteorological stations. Under SSP5-

Table 5: SDSM-based evaluation metrics of each station during the phases of calibration (1983–2000) and validation (2001–2014)

Periods	Predictand	Evaluation index	Meteorological station					
			AL0019	AL0035	AL0053	AL0057	AL0059	AL0066
Calibration (1983-2000)	Maximum Temperature	R^2	0.997	0.996	0.985	0.986	0.991	0.992
		RMSE	1.102	0.051	0.032	0.044	0.057	0.038
		Pbias (%)	4.653	0.092	– 0.012	– 0.056	– 0.031	0.084
		NSE	0.988	1.000	1.000	1.000	1.000	1.000
	Minimum temperature	R^2	0.995	0.996	0.989	0.987	0.986	0.992
		RMSE	0.105	0.043	0.052	0.075	0.035	0.040
		Pbias (%)	0.490	0.612	– 1.773	0.341	0.312	– 0.896
		NSE	1.000	1.000	1.000	1.000	1.000	1.000
Validation (2001-2014)	Maximum Temperature	R^2	0.998	1.000	1.000	1.000	1.000	1.000
		RMSE	0.964	0.124	0.097	0.119	0.103	0.098
		Pbias (%)	1.374	0.197	0.242	0.328	0.151	0.010
		NSE	0.991	1.000	1.000	1.000	1.000	1.000
	Minimum temperature	R^2	1.000	1.000	1.000	1.000	0.999	1.000
		RMSE	0.320	0.209	0.199	0.197	0.238	0.192
		Pbias (%)	0.923	1.752	0.926	0.432	– 0.570	– 0.282
		NSE	1.000	1.000	1.000	1.000	1.000	1.000

8.5, Tmin is expected to rise by 2.55°C, 2.65°C, 2.74°C, 1.74°C, and 3.04°C in 2061–2080, and by 4.07°C, 4.81°C, 4.54°C, 2.91°C, and 4.84°C in 2081–2100 for ACCESS-CM2, HadGEM3-GC31-LL, EC-Earth3-Veg, MRI-ESM2-0, and UKESM1-0-LL, respectively. Under SSP2-4.5, Tmin is projected to increase by 1.64°C, 1.42°C, 1.40°C, 0.40°C, and 1.59°C in 2061–2080, and by 2.77°C, 3.11°C, 2.09°C, 1.86°C, and 2.93°C in 2081–2100 for the same GCMs, relative to the reference period. It is expected that temperature fluctuations during the far-future period (2081–2100) will demonstrate a more pronounced increase in warming than those observed in the mid-future period (2061–2080), underscoring the intensifying influence of climate change over time. This study evaluated weather conditions, specifically maximum and minimum air temperatures, using data from five CMIP6 GCMs across six weather stations in the ZRB. The performance of the GCMs was assessed using Taylor diagrams, with a primary focus on the evaluation metric R^2. Most of the CMIP6 GCMs showed a significant correlation with the observed temperature data. The results highlighted that two models, HadGEM3-GC31-LL and UKESM1-0-LL, showed the highest rates of temperature increase in the region. Figs. 4, 5, 6 and 7 illustrate the percentage changes in the projected mean monthly maximum and minimum temperatures from 2015 to 2100, relative to the baseline period (1983–2014).

An analysis of the modeled maximum temperatures reveals a uniform upward trend throughout the years for both SSP2-4.5 and SSP5-8.5 scenarios in comparison to the reference period from 1983 to 2014. By 2100, the annual maximum temperature is projected to rise between 3.96°C and 4.91°C under SSP2-4.5 and between 5.5°C and 6.2°C under SSP5-8.5, depending on the climate model. Similarly, the annual minimum temperature is expected to increase, ranging from 4.99°C to 6.09°C under SSP2-4.5. Specifically, the yearly minimum temperatures are projected to rise by 6.99°C, 7.53°C, 7.2°C, 7.1°C, and 7.64°C for the models ACCESS-CM2, HadGEM3-GC31-LL, EC-Earth3-Veg, MRI-ESM2-0, and UKESM1-0-LL, respectively, under SSP2-4.5. These projections align with the ongoing warming trend observed in the ZRB throughout the 21st century, as highlighted in this study. The temperature predictions outlined in this study are in agreement with prior studies conducted in diverse areas. For instance, Enyew *et al.* (2024) observed a significant increase in temperatures across all zones under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, with statistical significance ($p < 0.01$). In the UBNB region, the average annual maximum temperature is expected to rise by 1.8°C, 2.1°C, and 2.8°C under SSP1-2.6, SSP2-4.5, and SSP5-8.5 from 2015 to 2100. Similarly, the average annual minimum temperature is projected to increase by 1.5°C, 2.1°C, and 3.1°C under these respective scenarios. The considerable transformations in climate conditions are projected to influence the occurrence and intensity of extreme events, emphasizing the importance for communities

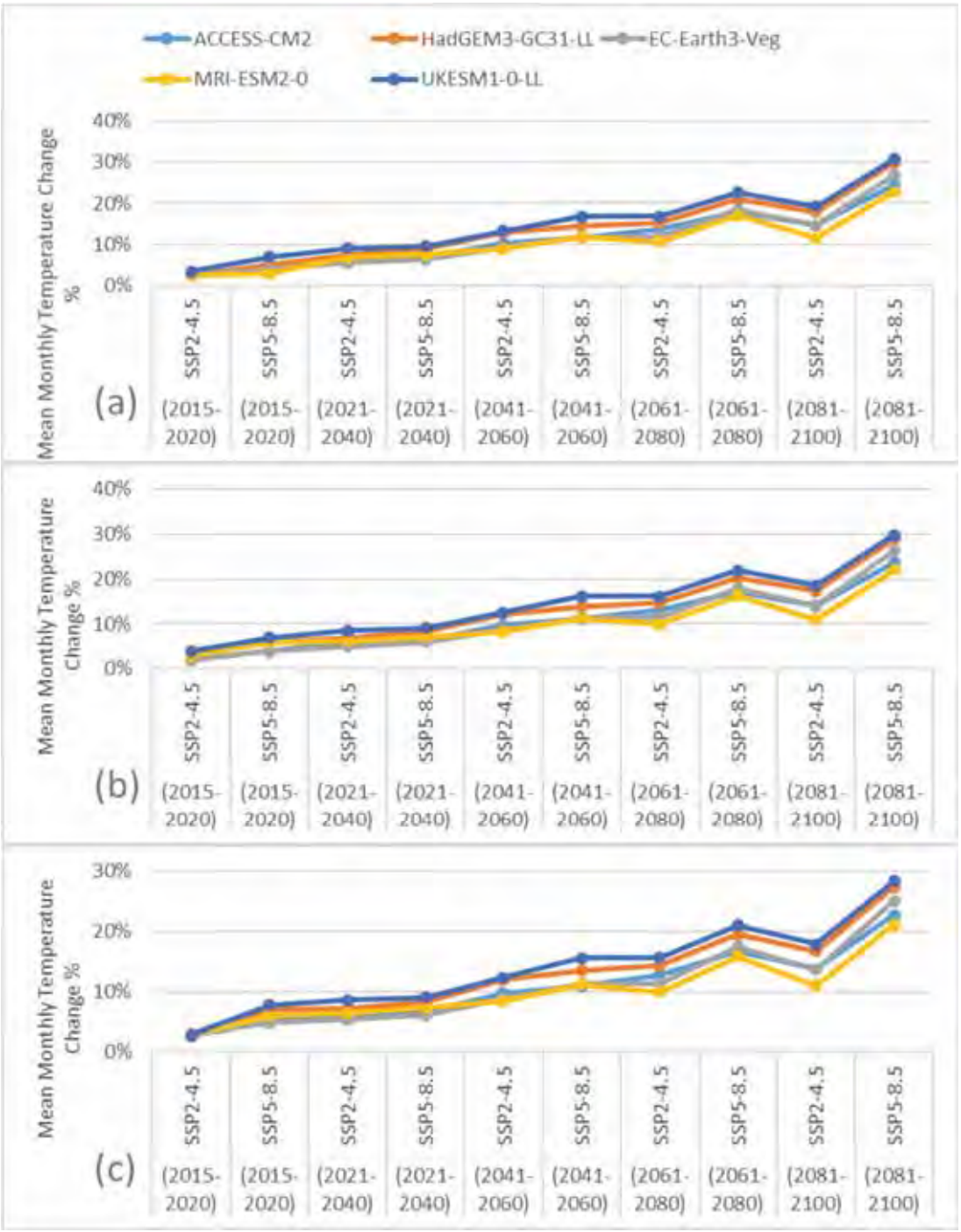


Fig. 4: Mean monthly change in projected Tmax in 2015-2100 under two SSPs scenarios with respect to the baseline (1983-2014) at (a) AL0019, (b) AL0035 and (c) AL0053 stations

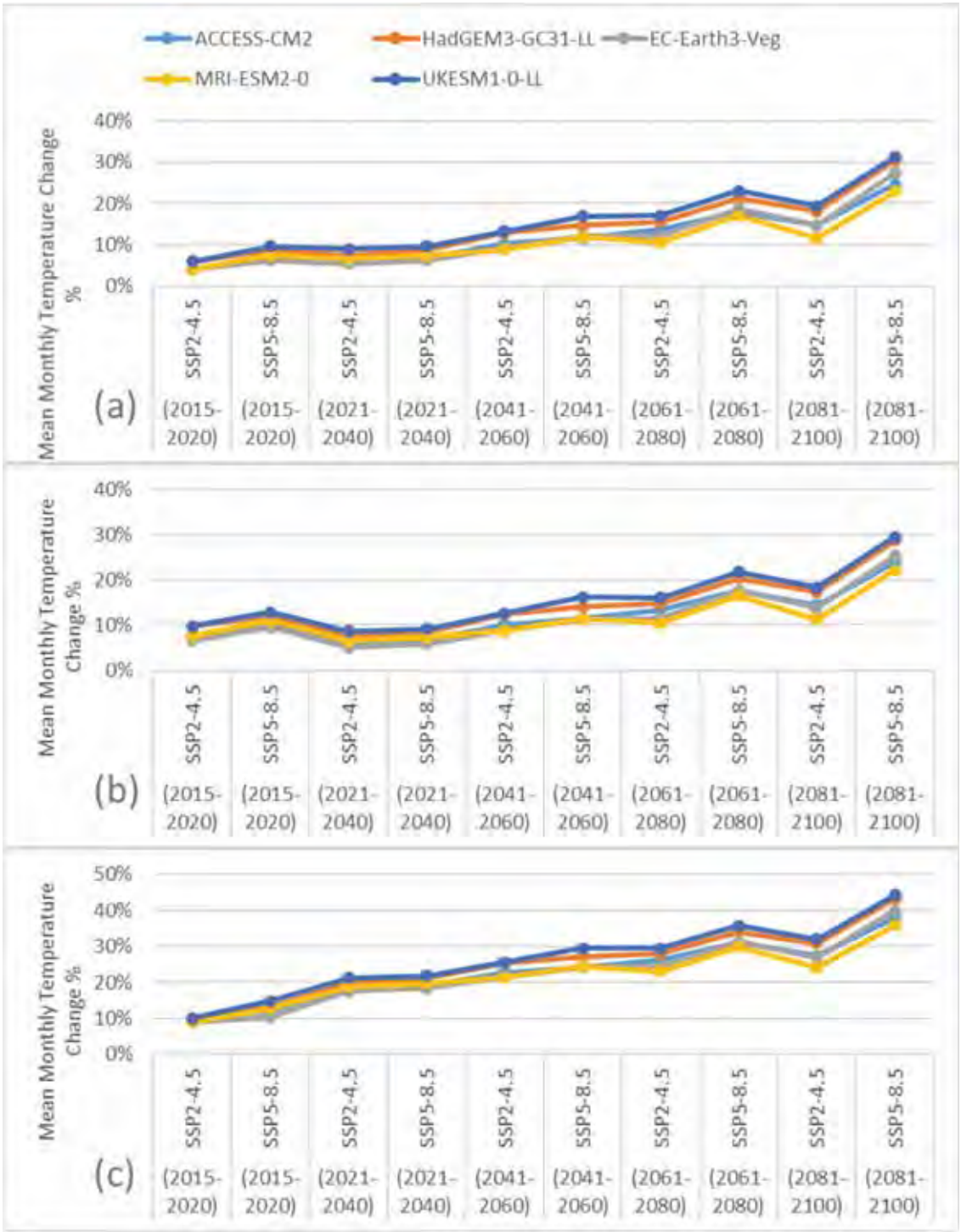


Fig. 5: Mean monthly change in projected Tmax in 2015-2100 under two SSPs scenarios with respect to the baseline (1983-2014) at (a) AL0057, (b) AL0059 and (c) AL0066 stations

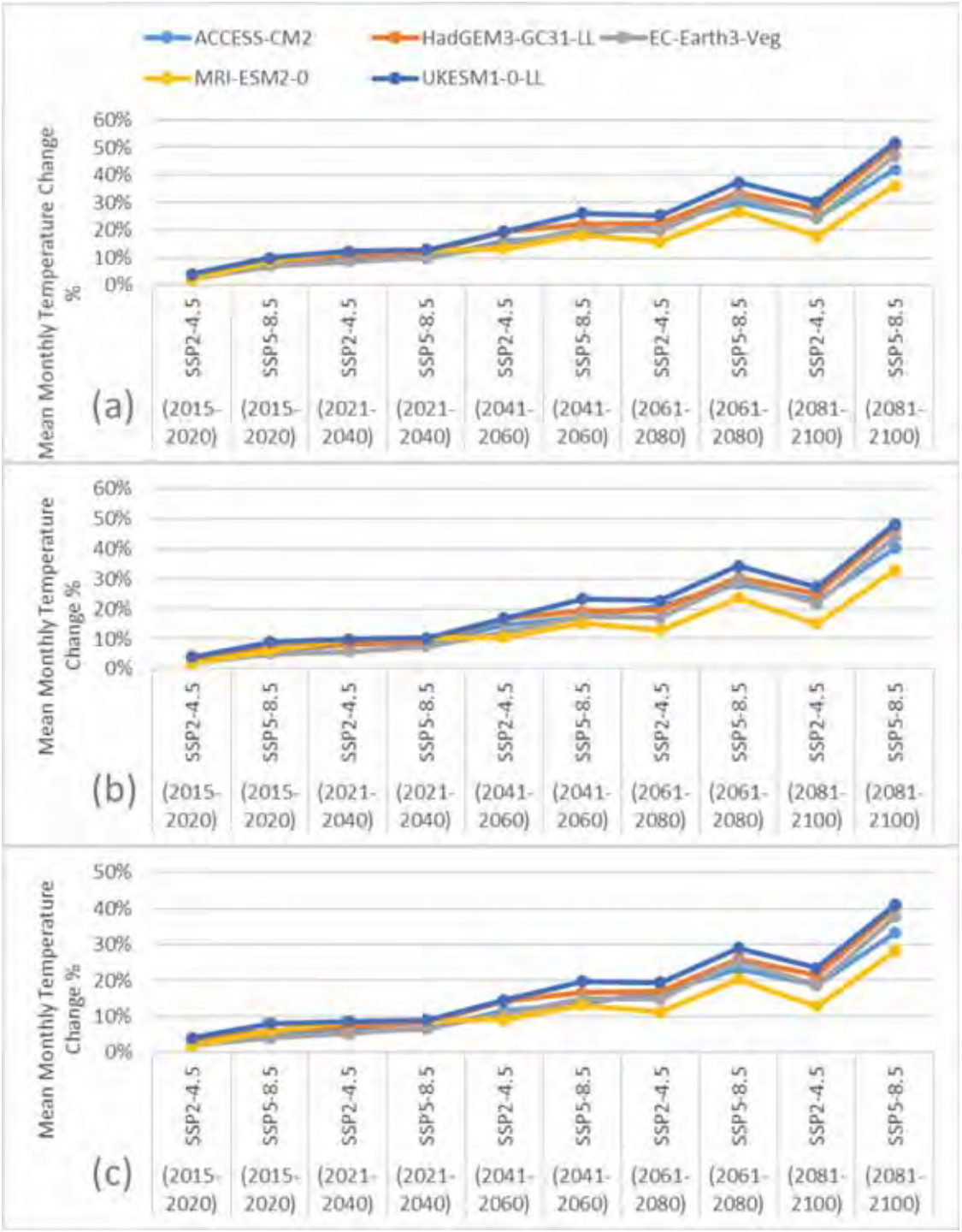


Fig. 6: Mean monthly change in projected Tmin in 2015-2100 under two SSPs scenarios with respect to the baseline (1983-2014) at (a) AL0019, (b) AL0035 and (c) AL0053 stations

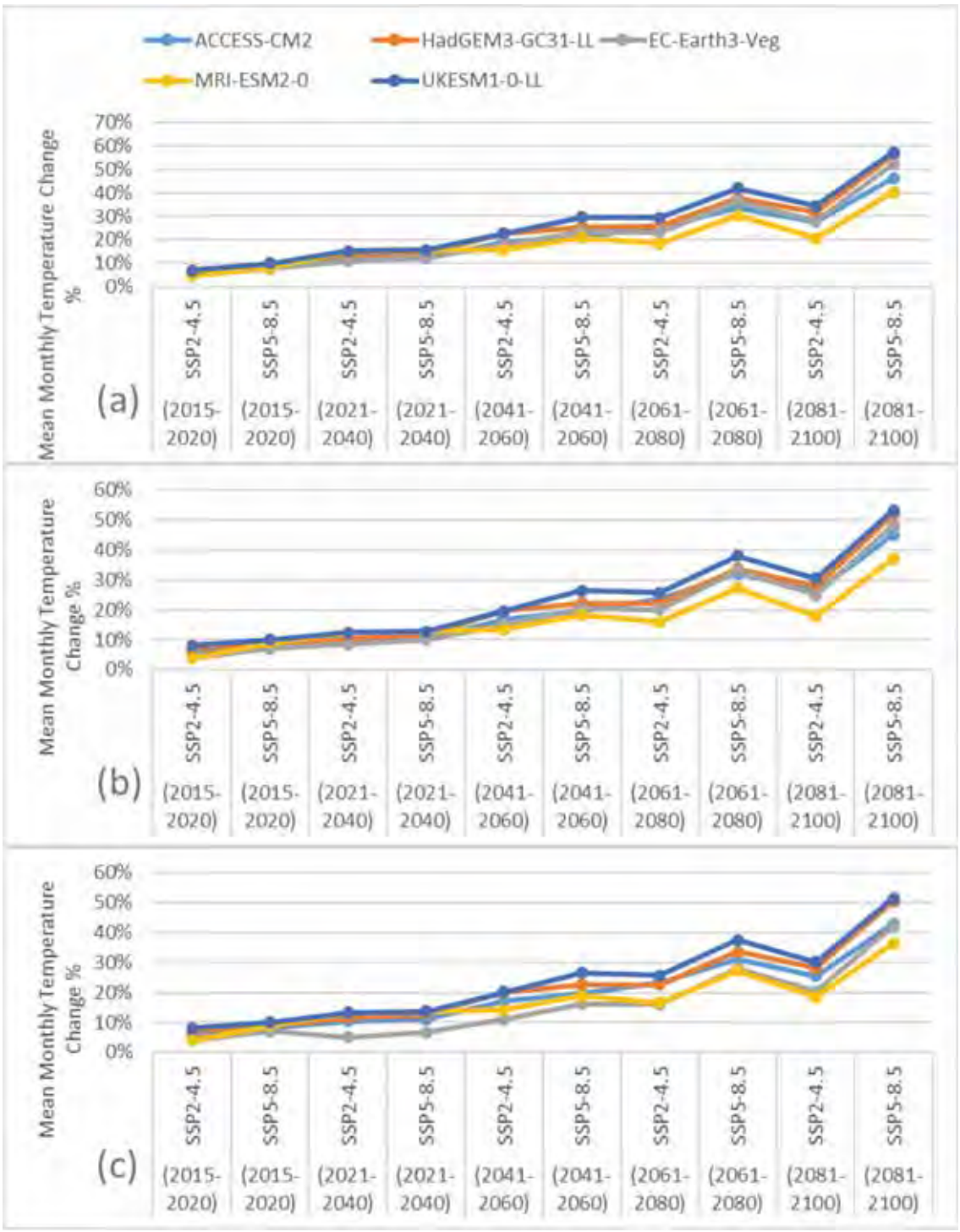


Fig. 7: Mean monthly change in projected Tmin in 2015-2100 under two SSPs scenarios with respect to the baseline (1983-2014) at (a) AL0057, (b) AL0059 and (c) AL0066 stations

to adopt a range of adaptation strategies to reduce the impacts of escalating temperatures. Getachew *et al.* (2021) projected a temperature rise of 1.38–3.59°C by the 2080s in the Lake Tana sub-basin of Ethiopia under the RCP4.5 radiative forcing scenario. Rising temperatures are associated with numerous significant consequences. Agarwal (2020) conducted meteorological forecasting using temperature data from 1969-2009 and rainfall data from 1981-2016. For the SDSM prediction process, historical data from the CANESM2 GCM spanning 1961 to 2005 was utilized, alongside RCP scenarios extending from 2006 to 2100, based on projections from the IPCC. The results indicated that temperatures and precipitation events would increase rapidly in the coming years. For example, between 2081-2084, RCP 8.5 projected a peak average temperature of 30.5°C, while RCP 2.6 experienced fewer extreme temperature events compared to the other scenarios. The SDSM demonstrated strong modeling performance for both minimum and maximum temperatures during the calibration (1983-2000) and validation (2001-2014) phases, with R2 and NSE values greater than 0.957. The SDSM demonstrated significant efficacy in modeling temperature patterns. Similarly, the CMIP6 GCMs showed a significant correlation with temperature measurements in the ZRB. The proficiency of CMIP6 GCMs in simulating extreme temperature patterns can be linked to improvements in parameterization methods, higher spatial resolution, and a more effective representation of physical processes, as emphasized by Eyring *et al.* (2016). In addition to annual trends, this study examined seasonal temperature variations, revealing more pronounced warming during the summer months under both SSP2-4.5 and SSP5-8.5 scenarios. Seasonal shifts carry important consequences for water resources, with elevated summer temperatures potentially heightening evaporation rates and worsening water stress during peak demand periods. Furthermore, temperature projections across the four time periods highlight progressive warming, with near-term increases (2015–2040) being less pronounced compared to mid-century and late-century projections. The changes observed over time emphasize the importance of taking prompt adaptive actions now, while also bracing for more intense effects down the line. The observed trends reflect the influence of emission trajectories and regional feedback mechanisms, which play critical roles in shaping the basin's future climate.

Projection of climatic variables

Figs. 8 and 9 illustrate the mean monthly changes in projected Tmax and Tmin under five CMIP6 GCMs (ACCESS-CM2, HadGEM3-GC31-LL, EC-Earth3-Veg, MRI-ESM2-0, and UKESM1-0-LL), respectively. These forecasts are assessed in relation to the baseline across four time frames (2015–2100), with the reference period set from 1983–2014. The analysis highlights the significant influence of SSP scenarios on temperature variations.

A variety of models often predict minimum temperatures that exceed the true figures, typically by a margin that is significantly larger than the biases seen in maximum temperature forecasts. This discrepancy arises from limitations in modeling convection and the inability to adequately capture topographic effects due to the models' coarse resolution (Kisembe *et al.*, 2019; Ongoma *et al.*, 2018). However, the ACCESS-CM2 model consistently performs well in replicating monthly Tmax and Tmin patterns in the ZRB, producing values closely aligned with observational data. The ACCESS-CM2 model's superior performance is due to innovations in the calculation of convection coefficients, better methodologies for estimating cloud fractions, and the inclusion of the indirect effects of aerosols on cloud formation and moisture convergence. These enhancements bolster its capability to model climatic conditions and provide a more precise representation of small-scale atmospheric dynamics (Seland *et al.*, 2020; Swart *et al.*, 2019).

Uncertainties in the downscaling process and biases in the models

Uncertainty is quantified using variance or its square root, which is referred to as the standard deviation (SD). Grasping these uncertainties is essential for climate change forecasts derived from multiple sources and is anticipated to support decision-makers in formulating strategies for adaptation and mitigation in an evolving climate. To assess the uncertainty during the baseline period of 1983-2014, the SD for the average monthly minimum and maximum temperatures were computed for each CMIP6 GCMs. The findings are illustrated in Table 6. The highest SD recorded was 7.872 °C for ACCESS-



Fig. 8: Mean monthly change in projected Tmax in periods of baseline (1983-2014) and future periods (2015-2100) under five CMIP6 GCMs Models

CM2, while the lowest was 5.61 °C for EC-Earth3-Veg. This suggests that ACCESS-CM2 demonstrated the highest degree of uncertainty when compared to the other GCMs. Uncertainties in the downscaling process and biases in GCMs significantly impact the accuracy of temperature projections. GCMs often simplify complex processes, such as cloud dynamics or land-atmosphere interactions, leading to coarse-scale biases. When data is downscaled, these biases can become more pronounced, particularly if statistical methods rely on historical data that inadequately represent future scenarios. Additionally, differences in GCM resolutions and assumptions about emissions pathways introduce variability. To enhance the reliability of climate projections for decision-making, it is important to address these challenges by utilizing sensitivity analyses, ensemble modeling, and improving methodologies.



Fig. 9: Mean monthly change in projected Tmin in periods of baseline (1983-2014) and future periods (2015-2100) under five CMIP6 GCMs Models

Table 6: The SD for monthly Tmin and Tmax (℃) at six meteorological stations for each CMIP6 GCMs Model

Temperature	Stations	ACCESS-CM2	HadGEM3-GC31-LL	EC-Earth3-Veg	MRI-ESM2-0	UKESM1-0-LL
Tmin	AL0019	± 6.0	± 5.9	± 5.9	± 5.9	± 5.9
	AL0035	± 5.7	± 5.7	± 5.6	± 5.6	± 5.6
	AL0053	± 5.8	± 5.7	± 5.7	± 5.7	± 5.7
	AL0057	± 5.8	± 5.7	± 5.7	± 5.7	± 5.7
	AL0059	± 6.2	± 6.1	± 6.0	± 6.1	± 6.1
Tmax	AL0019	± 7.6	± 7.6	± 7.5	± 7.5	± 7.5
	AL0035	± 7.4	± 7.4	± 7.3	± 7.3	± 7.3
	AL0053	± 6.8	± 6.8	± 6.7	± 6.7	± 6.7
	AL0057	± 7.4	± 7.3	± 7.3	± 7.3	± 7.3
	AL0059	± 7.9	± 7.8	± 7.7	± 7.8	± 7.8

CONCLUSION

This study successfully developed and applied a reconstructed SDSM using data from five carefully selected GCMs—ACCESS-CM2, HadGEM3-GC31-LL, EC-Earth3-Veg, MRI-ESM2-0, and UKESM1-0-LL. Future climate projections were downscaled for two significant Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) by employing the MIROC6 and MRI-ESM2.0 models, respectively. According to the downscaled CMIP6 models, the ZRB is projected to face an increasingly arid and warmer climate as the 21st century progresses, with notable temperature increases expected by the century's end (2100) relative to the mid-century mark (2050). These findings underline the increasing likelihood of significant climate changes in the region, which will have far-reaching implications for water resource availability and ecosystem sustainability. According to the results derived from the downscaled CMIP6 models, the ZRB is projected to undergo notable transformations. The research offered a thorough assessment of Tmax and Tmin temperature changes in the ZRB, a region where the sustainable management of water resources is vital due to conflicting demands. During the baseline period (1983–2014), the five selected CMIP6 GCMs were assessed for their accuracy in replicating observed temperature trends under two scenarios: SSP2-4.5, representing a medium-emission pathway, and SSP5-8.5, representing a high-emission pathway. Among the models, HadGEM3-GC31-LL and UKESM1-0-LL demonstrated the best performance in simulating Tmax and Tmin trends with strong alignment to actual observations. Predictions show that both maximum and minimum temperatures are expected to experience regular and considerable annual growth under each emission scenarios. By 2100, annual maximum temperature increases are projected to range between 3.96°C and 4.91°C under SSP2-4.5, and between 5.5°C and 6.2°C under SSP5-8.5. Similarly, annual minimum temperature increases under SSP2-4.5 are estimated to range from 4.99°C to 6.09°C, while under SSP5-8.5, specific increases are projected for each GCM: 6.99°C (ACCESS-CM2), 7.53°C (HadGEM3-GC31-LL), 7.2°C (EC-Earth3-Veg), 7.1°C (MRI-ESM2-0), and 7.64°C (UKESM1-0-LL). The observed trends are in agreement with the continuous global and regional warming experienced in the 21st century, implying a strengthening of extreme temperature patterns in the ZRB. Future research should integrate land use and land cover and socio-economic parameters to enhance understanding of climate impacts and support holistic adaptation and mitigation strategies. This study's findings offer significant insights into the effects of climate change on the ZRB, delivering crucial data for hydrological and environmental modeling. Rising temperatures may increase evaporation, reduce water availability, and intensify droughts. In agriculture, heat stress could lower crop yields, while biodiversity may face habitat shifts and increased species vulnerability. Although this sudy is centered on temperature, the interaction between variations in temperature and precipitation patterns, as well as their collective influence on water availability and ecosystem dynamics, calls for further study. These interconnections highlight the need for integrated climate adaptation strategies. Future research will incorporate additional climate variables and their interactions to provide a more comprehensive understanding of climate change impacts on the basin's hydrology and ecosystems. Temperature projections are influenced by local factors including elevation, the closeness of water bodies, and the degree of urbanization. Higher elevations cool more slowly, water bodies moderate temperature changes, and urbanization amplifies warming via the heat island effect. Future studies should integrate these factors for enhanced projections. Temperature projections for the ZRB are consistent with warming trends observed in other arid regions under SSP2-4.5 and SSP5-8.5, suggesting shared climate vulnerabilities. Additionally, the positioning of stations plays a crucial role in the accuracy of projections, with factors such as altitude and regional climate trends causing observed discrepancies. Subsequent studies should aim to refine spatial analyses to enhance the dependability of the models. These findings can support the development of evidence-based policies for drought monitoring, water resource management, and long-term sustainability planning in the region. The significant temperature increases projected in this study emphasize the urgency of adaptive water management strategies in the ZRB. Potential measures include promoting water-use efficiency through modern irrigation systems, enhancing water recycling and reuse, and adopting drought-resistant agricultural practices. An expected rise in minimum temperatures in the ZRB may contribute to higher

rates of evapotranspiration, which in turn could lead to increased water demand for agricultural purposes and various other applications. These changes could shift growing seasons, affecting crop productivity and suitability for traditional agricultural practices. Ecosystem-based strategies, such as afforestation and watershed management, can also reduce vulnerability to temperature-induced stress. To effectively embed these strategies within regional policies, it is essential to engage stakeholders, enhance capacity building, and offer financial incentives that encourage their implementation. By addressing the dual challenges of water scarcity and rising temperatures, these measures can support long-term sustainability in the basin.

AUTHOR CONTRIBUTIONS

H. Hroub contributed to the conceptualization, methodology and performed formal analysis of the study. M. Rahbeh managed the project administration and provided supervision throughout the study. M.M. Zoubi was involved in the investigation, validation and original draft preparation. Q.Y. Abu-Afifeh provided resources and was responsible for data curation. H. Al-Jawaldeh handled the software and visualization aspects of the study. N. Obeidat was in charge of reviewing and editing the manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The authors. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
°C	degrees Celsius
ACCESS-CM2	Australian Community Climate and Earth System Simulator
AL0019	Amman Airport
AL0035	K.H. Nursery Evap.St
AL0053	King talal dam
AL0057	Wadi Es-Sir
AL0059	Um El-Jumal Evap .St
AL0066	Khirebit Es Samra Evap .St
AOGCM	Atmosphere-Ocean General Circulation Model
CMIP5	Coupled model intercomparison project 5
CMIP6	Coupled model intercomparison project 6
DOS	Jordanian Department of Statistics
E	East
EC-Earth3-Veg	Earth consortium version 3 - vegetation
ESGF	Earth Systems Grid Federation
ESM	Earth system model
GCMs	General circulation models
HadCM3	Hadley Centre Coupled Model 3
HadGEM3-GC31-LL	Hadley centre global environmental model 3—Global coupled configuration 3.1
hPa	HectoPascals
km	Kilometer
LARS-WG	Long Ashton Research Station Weather Generator

m	Meter
mm	Millimeter
MRI-ESM2-0	Meteorological Research Institute
MRI-ESM2-0	Meteorological Research Institute
mslp	Mean sea level pressure
MWI	Ministry of Water and Irrigation
N	North
n	the total number of observed data points
NCEP/NCAR	National Center for Environmental Prediction/ Atmospheric Research
NSE	Nash–sutcliffe efficiency
p__z	1,000 hPa vorticity
p_f	1,000 hPa wind speed
p_th	1,000 hPa wind direction
p_u	1,000 hPa zonal velocity
p_v	1,000 hPa meridional velocity
p_zh	1,000 hPa divergence
p5_f	500 hPa wind speed
p5_u	500 hPa zonal velocity
p5_v	500 hPa meridional velocity
p5_z	500 hPa vorticity
p500	500 hPa geopotential height
p5th	500 hPa wind direction
p5zh	500 hPa divergence
p8_f	850 hPa wind speed
p8_u	850 hPa zonal velocity
p8_v	850 hPa meridional velocity
p8_z	850 hPa vorticity
p850	850 hPa geopotential height
p8th	850 hPa wind direction
p8zh	850 hPa divergence
Pbias	bias correction
prep	Precipitation
R^2	coefficient of determination
r500	500 hPa specific humidity
r850	850 hPa specific humidity
RMSE	root mean square error
SDSM	Statistical downscaling models
Shum	1,000 hPa specific humidity
SSPs	Socio-economic pathways
SD	Standard deviation
temp	Screen (2 m) air temperature
Tmax	maximum air temperature
Tmin	minimum air temperature
UKESM1-0-LL	UK Earth System Modelling Project
Xmi	the modeled outcome for day iii
Xoi	the observed prediction for day iii
$\bar{X}oi$	the average of measured values over the study period
ZRB	Zarqa River Basin

REFERENCES

Abbass, K.; Qasim, M.Z.; Song, H., (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ. Sci. Pollut. Res., 29: 42539–42559 **(21 pages).**

Abu-Afifeh, Q.; Rahbeh, M.; Al-Afeshat, A.; Al-Omari, S.; Qutishat, T.A.; Brezat, A.; Alkayed, A., (2023). Dam sustainability's interdependency with climate change and dam failure drivers. Sustainability, 15: 1–19 **(19 pages).**

Agarwal, S., (2020). Statistical downscaling of temperature and precipitation using SDSM. Proceeding of national Conference on Emerging Trends in Civil Engineering. 856-862 **(7 pages)**.

Al-Afeshat, A.; Zoubi, M.M.; Abu-Afifeh, Q.Y.; Al-Jawaldeh, H.; Qutishat, T.A.; Masoud, A.M.N.;, Rahbh, M., (2025). Interrelation of dams sustainability with the local communities and water quality. Global J. Environ. Sci. Manage., 11(1): 157-176 **(20 pages).**

Al Saodi, R.; Al Kuisi, M.; Al Salaymeh, A., (2023). Assessing the vulnerability of flash floods to climate change in arid zones: Amman–Zarqa Basin, Jordan. J. Water Clim. Change, 14(12): 4376–4403 **(29 pages).**

Al-Hasani, I.; Al-Qinna, M.I.; Hammouri, N.A., (2023). Potential impacts of climate change on surface water resources in arid regions using downscaled regional circulation model and soil water assessment tool, a case study of Amman-Zerqa Basin, Jordan. Clim., 11(51): 1-24 **(24 pages).**

Almazroui, M.; Saeed, F.; Saeed, S., (2020). Projected change in temperature and precipitation over africa from CMIP6. Earth Syst. Environ., 4: 455–475 **(21 pages).**

Arshad, M.; Ma, X.; Yin, J.; Ullah, W.; Liu, M.; and Ullah, I., (2021). Performance evaluation of ERA-5, JRA-55, MERRA-2, and CFS-2 reanalysis datasets, over diverse climate regions of Pakistan. Weather Clim. Extremes. 33: 100373 **(17 pages).**

Buda, Su.; Huang, J.; Mondal, S.;Tong, J., (2020). Insight from CMIP6 SSP-RCP scenarios for future drought characteristics in China. Atmos. Res., 250: 1-17 **(17 pages).**

Choi, B.; Bergés, M.; Bou-Zeid, E.; Pozzi, M., (2021) Short-term probabilistic forecasting of meso-scale near-surface urban temperature fields. Environ. Model. Softw., 145: 105189 **(19 pages).**

Clarke, B.; Otto, F.; Stuart-Smith, R.; Harrington, L., (2022). Extreme weather impacts of climate change: an attribution perspective. Environ. Res. Clim., 1(1): 1-25 **(25 pages).**

Dibaba, W, T.; Demissie, T, A.; Miegel, K., (2020). Watershed hydrological response to combined land use/land cover and climate change in Highland Ethiopia: Finchaa Catchment. Water. 12(6): 1-25 **(25 pages).**

Dixon, K.W.; Lanzante, J.R.; Nath, M.J., (2016). Evaluating the stationarity assumption in statistically downscaled climate projections: is past performance an indicator of future results?. Clim. Change. 135: 395–408 **(14 pages).**

El-Samra, R.; Haddad, A.; Alameddine, I.; Bou-Zeid, E.; El-Fadel, M., (2024). Downscaling climatic variables at a river basin scale: statistical validation and ensemble projection under climate change scenarios. Clim., 12: 27 **(23 pages).**

Enyew, F.B.; Sahlu, D.; Tarekegn, G, B.; Hama, S.; Debele, S, E., (2024). Performance evaluation of cmip6 climate model projections for precipitation and temperature in the Upper Blue Nile Basin, Ethiopia. Clim., 12(11): 169 **(22 pages).**

Eyring, V.; Bony, S.; Meehl, G.A.; Senior, C.A.; Stevens, B.; Stouffer, R.J.; Taylor, K.E., (2016). Overview of the coupled model intercompar-ison project phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev., 9: 1937–1958 **(21 pages).**

Farzaneh, M.; Banimostafaarab, F.; Hamarashid. S.H., (2024). Preservation and restoration of Hamoun Wetland: a Joint Solution for Iran and Afghanistan in the field of facing the climate change phenomenon. J. Drought Clim. Change Res., 15-38 **(25 pages).**

Fenta Mekonnen, D.; Disse, M., (2018). Analyzing the future climate change of Upper Blue Nile River Basin using statistical downscaling techniques. Hydrol. Earth Syst. Sci., 22: 2391–2408 **(18 pages).**

Feyissa, T.A.; Demissie, T.A.; Saathoff, F.; Gebissa, A., (2023). Evaluation of general circulation models CMIP6 performance and future climate change over the Omo River Basin, Ethiopia. Sustainability. 15: 6507 **(37 pages).**

GCF, (2022). Green climate facts, Jordan.

Gebrechorkos, S.H.; Hülsmann, S.; Bernhofer, C., (2019). Statistically downscaled climate dataset for East Africa. Sci. Data. 6: 31 **(8 pages).**

Getachew, B.; Manjunatha, B, R., (2021). Future climate change projection and trends under CMIP5 in Lake Tana basin, Upper Blue Nile River Basin, Ethiopia. Environ. Challenges. 5: 1-22 **(22 pages).**

Ghazi, B.; Jeihouni, E., (2022). Projection of temperature and precipitation under climate change in Tabriz, Iran. Arab J. Geosci.,15: 621 **(11 pages).**

Giorgi, F., (2019). Thirty years of regional climate modeling: where are we and where are we going next?. J. Geophys. Res.:Atmos., 124: 5696–5723 **(28 pages).**

Grose, M.R.; Narsey ,S.; Delage, F.;Dowdy ,AJ.; Bador. M.; Boschat, G.; Chung,C.; Kajtar ,J.; Rauniyar S.; Freund, M., (2020). Insights from CMIP6 for Australia's future climate. Earth Future. 8(5): e2019EF001469 **(24 pages).**

Hamed, M.; Iqbal, Zafar.; Nashwan, M.; Kineber, A.; Shahid, Sh., (2023). Demising evapotranspiration paradox and its cause in the Middle East and North Africa. Atmos. Res., 289: 106760 **(24 pages).**

Hamed, M.; Nashwan, M.; Shahid,S., (2021). Performance evaluation of reanalysis precipitation products in Egypt using fuzzy entropy time series similarity analysis. Int. J. Climatol., 41(11): 5431–5446 **(15 pages).**

Hassan, Z.; Shamsudin, S.; Harun, S., (2014). Application of SDSM and LARS-WG for simulating and downscaling of rainfall and temperature. Theor. Appl. Climatol., 116: 243–257 **(14 pages).**

Huseynov, J.; Tagiyev, A., (2024). The changes of the air temperature characteristics in the Azerbaijan territory during global climate changes period. Visnyk of Taras Shevchenko National University of Kyiv. Geology. 3: 76-82 **(7 pages).**

Hyarat,T.; Al Kuisi,M.; Saffarini,G., (2022). Assessment of groundwater quality using water quality index (WQI) and multivariate statistical analysis in Amman-Zarqa area/Jordan. Water Pract. Technol., 17 (8): 1582–1602 **(21 pages).**

IPCC, (2014). Climate Change 2014: Synthesis report. In: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.151 (Pachauri, R.K. and Meyer, L.A., eds.). IPCC, Geneva, Switzerland.

Jain, S.; Salunke, P.; Mishra, S. K.; Sahany, S., (2019). Performance of CMIP5 models in the simulation of Indian summer monsoon. Theor. Appl. Climatol., 137:1429–1447 **(20 pages).**

Jose, D.M.; Dwarakish G, S., (2022) . Bias correction and trend analysis of temperature data by a high-resolution CMIP6 model over a Tropical River Basin. Asia-Pac. J. Atmos. Sci., 58 (1): 97–115 **(18 pages).**

Kisembe, J.; A, Favre.; A, Dosio.; C, Lennard.; G, Sabiiti.; A, Nimusiima., (2019). Evaluation of rainfall simulations over Uganda in CORDEX regional climate models. Theor. Appl. Climatol., 137: 1117–1134 **(18 pages).**

Kloub, A.; Alzboon, K., (2023). Impact of climate change on groundwater resources in Jordan: a case study of Amman Zarqa basin. Res. Square. 1-30 **(30 pages).**

Knutti, R., (2008).Why are climate models reproducing the observed global surface warming so well?. Geophys. Res. Lett., 35: 18 **(5 pages).**

Kraaijenbrink, P.D.; Bierkens, M.; Lutz, A.; Immerzeel, W., (2017). Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. Nat., 549 (7671): 257–260 **(4 pages).**

Kumar, P.; Barat, A.; Sarthi, P.P., (2024). Evaluating future urban temperature over smart cities of the Gangetic plains using statistically downscaled CMIP6 projections. Theor. Appl. Climatol., 155:4585–4600 **(15 pages).**

Kundu, S.; Khare, D.; Mondal, A., (2017). Future projection of rainfall by statistical downscaling method in a part of central India. In: Hazra, S., Mukhopadhyay, A., Ghosh, A., Mitra, D., Dadhwal, V. (eds) Environment and earth observation. Springer Remote Sensing/Photogrammetry. Springer, Cham. **(23 pages).**

Latif, Y.; Yaoming, M.; Yaseen, M.; Muhammad, S.;Wazir, M. A.,(2019) . Spatial analysis of temperature time series over the Upper Indus Basin (UIB) Pakistan. Theor. Appl. Climatol., 139: 741–758 **(18 pages).**

Lin, Q., Chen, J.; Li,W.; Huang, K.; Tan, X.; Chen, H., (2021). Impacts of land use change on thermodynamic and dynamic changes of precipitation for the Yangtze River Basin, China. Int. J.

Climatol.,41: 3598–3613 **(16 pages).**

Lu, K.; Arshad, M.; Ma, X.; Ullah, I.; Wang, J.; Shao, W., (2022). Evaluating observed and future spatiotemporal changes in precipitation and temperature across China based on CMIP6-GCMs. Int. J. Climatol., 42(15): 7703–7729 **(26 pages).**

Lun,Y.; Liu ,L.; Cheng, L.; Li ,X.; Li ,H.; and Xu ,Z., (2021). Assessment of GCMs simulation performance for precipitation and temperature from CMIP5 to CMIP6 over the Tibetan Plateau. Int. J. Climatol., 41(7): 3994–4018 **(22 pages).**

Mahamid, J.S., (2005). Integration of water resources of the upper aquifer in Amman-Zarqa Basin based on mathematical modeling and GIS, Jordan. Freiberg Geosci., 1-218 **(218 pages).**

Maraun, D.; F, Wetterhall.; A. M, Ireson.; R. E, Chandler.; E. J, Kendon.; M, Widmann.; S, Brienen, H. W, Rust.; T, Sauter.; M, Themeßl.;V. K. C, Venema.; K. P, Chun.; C. M, Goodess.; R. G, Jones C Onof, M. Vrac, I., (2010). Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamic models and the end user. Rev. Geophys., 48: 3 **(34 pages).**

Meenu, R.; Rehana, S.; Mujumdar, P. P., (2013). Assessment of hydrologic impacts of climate change in Tunga-Bhadra River basin, India with HEC-HMS and SDSM. Hydrol. Processes. 27(11): 1572–1589 **(17 pages).**

Ngoma ,H.; Wen, W.; Ayugi ,B.; Babaousmail, H.; Karim R.; Ongoma ,V., (2021). Evaluation of precipitation simulations in CMIP6 models over Uganda. Int. J. Climatol., 41(9): 4743–4768 **(25 pages).**

Noël ,T.; Loukos, H.; Defrance, D.;Vrac ,M.; Levavasseur, G., (2022). Extending the global high-resolution downscaled projections dataset to include CMIP6 projections at increased resolution coherent with the ERA5-Land reanalysis. Data Brief. 45: 108669 **(10 pages).**

Obeidat, N.; Shatanawi, K.; Kassab, G.; Halalsheh, M., (2024). Performance of decentralized wastewater treatment system employing upflow anaerobic sludge blanket and vertical flow constructed wetland. Case Stud. Chem. Environ. Eng., 9: 1-10 **(10 pages).**

Ongoma, V.; Chen, H.; Gao, C.; Nyongesa, AM.; Polong, F., (2018). Future changes in climate extremes over Equatorial East Africa based on CMIP5 multimodel ensemble. Nat. Hazards. 90(2018): 901–920 **(19 pages).**

Onyutha, C.; Asiimwe, A.; Ayugi, B.; Ngoma, H.; Ongoma,V.; Tabari, H.,(2021) Observed and future precipitation and evapotranspiration in water management zones of Uganda: CMIP6 Projections. Atmospheres. 12(7): 887 **(25 pages).**

Peng, J.; Dan, L.; Yang, F.; Tang, X.; and Wang, D., (2021). Global and regional estimation of carbon uptake using CMIP6 ESM compared with TRENDY ensembles at the centennial scale. J. Geophysical Res. Atmos., 126 **(14 pages).**

Pomee, M.S.; Hertig E., (2021). Temperature projections over the Indus River basin of Pakistan using statistical downscaling. Atmospheres. 12(2): 195 **(32 pages).**

Rana, M.; Adhikary, S.K.; Islam, M.B., (2024). Assessment of future climate change over the north-west region of Bangladesh using SDSM and CanESM2 under RCP scenarios. Arab J. Geosci., 17: 280 **(19 pages).**

Rathinasamy, M.; R. Khosa, J.; Adamowski, S.; ch, G, Partheepan.; J, Anand.; B, Narsimlu., (2014). Wavelet-based multiscale performance analysis: An approach to assess and improve hydrological models. Water Resour. Res., 50: 9721–9737 **(17 pages).**

RCCC, (2022). Jordan climate factsheet.

Richter, I.; Tokinaga, H., (2020). An overview of the performance of CMIP6 models in the tropical Atlantic: mean state, variability, and remote impacts. Clim. Dyn., 55:579–2601 **(22 pages).**

Roy, A., (2024) A panel data study on the effect of climate change on life expectancy. PLOS Clim., 3(1): e0000339 **(21 pages).**

Gebrechorkos, S. H.; Hülsmann, S.; Bernhofer, C., (2018) . Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. Int. J. Climatol., 39 :18–30 **(12 pages).**

Salehie, O.; Hamed, M.M.; Ismail, T.b., (2023). Selection of CMIP6 GCM with projection of climate over the Amu Darya River Basin. Theor. Appl. Climatol., 151(2023): 1185–1203 **(18 pages).**

Samuels, R.; Rimmer,A.; Hartmann,A.; Krichak,S.; Alpert,P., (2010). Climate change impacts on Jordan River flow: downscaling application from a regional climate model. J. Hydrometeorol., 11: 860–879 **(20 pages).**

Schlund, M.; Lauer, A.; Gentine, P.; Sherwood, S.; Eyring, V., (2020). Emergent constraints on equilibrium climate sensitivity in CMIP5: do they hold for CMIP6?. Earth Syst. Dynam., 11: 1233–1258 **(26 pages).**

Seland, Ø.; Bentsen, M.; Olivié, D.; Toniazzo, T.; Gjermundsen, A.; Graff, L. S.; Debernard, J. B.; Gupta, A. K.; He, Y.-C.; Kirkevåg, A.; Schwinger, J.; Tjiputra, J.; Aas, K. S.; Bethke, I.; Fan, Y.; Griesfeller, J., Grini, A., Guo, C., Ilicak, M., Karset, I. H. H., Landgren, O., Liakka, J., Moseid, K. O., Nummelin, A.; Spensberger, C.; Tang, H.; Zhang, Z.; Heinze, C.; Iversen, T.; and Schulz, M., (2020). Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. Geosci. Model Dev., 13: 6165–6200 **(35 pages).**

Shawky, M.; Ahmed, M.; Ghaderpour, E.; Gupta, A.; Achari, G.; Hassan, Q., (2023). Remote sensing-derived land surface temperature trends over South Asia. Ecol. Inf., 74: 101969 **(15 pages).**

Swart, N. C.; Cole, J. N. S.; Kharin, V. V.; Lazare, M.; Scinocca, J. F.; Gillett, N. P.; Anstey, J.; Arora, V.; Christian, J. R.; Hanna, S.; Jiao, Y.; Lee, W. G.; Majaess, F.; Saenko, O. A.; Seiler, C.; Seinen, C.; Shao, A.; Sigmond, M.; Solheim, L.; von Salzen, K.; Yang, D.; and Winter, B., (2019).The Canadian Earth System Model version 5 (CanESM5.0.3), Geosci. Model Dev., 12: 4823–4873 **(50 pages).**

Thakor, H.B.; Parekh, F.P., (2024). Statistical Downscaling Model (SDSM) for Long Term Prediction of Rainfall and Maximum Temperature. In: Patel, D., Kim, B., Han, D. (eds) Innovation in smart and sustainable infrastructure. ISSI 2022. Lecture Notes Civil Eng., 364. Springer **(9 pages).**

Ullah, S.; You, Q.; Sachindra, D.A.; Nowosad, M.; Ullah, W.; Bhatti, A.S.; Jin, Z.; Ali, A., (2021). Spatiotemporal changes in global aridity in terms of multiple aridity indices: an assessment based on the CRU data. Atmos. Res., 268: 1-14 **(14 pages).**

Wilby, R.L.; Dawson, C.W.; Barrow, E.M., (2002). SDSM - a decision support tool for the assessment of regional climate change impacts, Environ. Modell. Softw., 17(2): 147–159 **(12 pages).**

Xu, Z.; Han, Y.; Tam, CY., (2021). Bias-corrected CMIP6 global dataset for dynamical downscaling of the historical and future climate (1979–2100). Sci. Data. 8: 293 **(11 pages).**

Xu, Y., (2019) .Estimates of changes in surface wind and temperature extremes in southwestern Norway using dynamical downscaling method under future climate. Weather Clim. Extremes. 26:

100234 **(16 pages).**

Zamani, Y.; Hashemi Monfared, S.; Azhdari moghaddam, M., (2020) . A comparison of CMIP6 and CMIP5 projections for precipitation to observational data: the case of Northeastern Iran. Theor. Appl. Climatol., 142: 1613–1623 **(10 pages).**

Zhang, Y.; You, Q.; Chen, C.; Ge, J., (2016). Impacts of climate change on streamflows under RCP scenarios: A case study in Xin River Basin, China. Atmos. Res., 178: 521–534 **(13 pages).**

Zhao, Y.; Qian, C; Zhang, W.; He, D.; Qi ,Y., (2021). Extreme temperature indices in Eurasia in a CMIP6 multi-model ensemble: Evaluation and projection. Int. J. Climatol., 41: 5368–5385 **(20 pages).**

Zittis, G.; Almazroui, M.; Alpert, P.; Ciais, P.; Cramer, W.; Dahdal, Y.; Fnais, M.; Francis, D.; Hadjinicolaou, P.; Howari, F., (2022) Climate change and weather extremes in the Eastern Mediterranean and MiddleEast. Rev. Geophys., 60(3): e2021RG000762 **(48 pages).**

AUTHOR (S) BIOSKETCHES

Hroub, H., Ph.D. Candidate, Instructor, Water and Environment Engineering, Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *haneenhroub835@gmail.com*
- ORCID: 0009-0008-6487-4301
- Web of Science ResearcherID: LXA-7755-2024
- Scopus Author ID: NA
- Homepage: https://agriculture.ju.edu.jo/Home.aspx

Rahbeh, M., Ph.D., Associate Professor, Agricultural Engineering, Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *m.rahbeh@ju.edu.jo*
- ORCID: 0000-0003-1270-5035
- Web of Science ResearcherID: H-2660-2019
- Scopus Author ID: 16040599200
- Homepage: https://eacademic.ju.edu.jo/m.rahbeh/default.aspx

Zoubi, M.M., M.Sc., Instructor, Chemistry, Department of Chemistry, The University of Jordan, Amman 11942, Jordan.
- Email: *mutazalzoubi@outlook.com*
- ORCID: 0009-0001-7719-8268
- Web of Science ResearcherID: LMP-2898-2024
- Scopus Author ID: 59008125300
- Homepage: https://science.ju.edu.jo/home.aspx

Abu-Afifeh, Q.Y., Ph.D., Instructor, Water and Environment Engineering, Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *qusayyabuafifeh@outlook.com*
- ORCID: 0000-0003-4451-3118
- Web of Science ResearcherID: LMO-4400-2024
- Scopus Author ID: 57219483554
- Homepage: https://agriculture.ju.edu.jo/Home.aspx

Al-Jawaldeh, H., Ph.D. Candidate, Instructor, Water and Environment Engineering, Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *jaloudiheba@gmail.com*
- ORCID: 0009-0008-0734-630X
- Web of Science ResearcherID: LMO-6478-2024
- Scopus Author ID: NA
- Homepage: https://agriculture.ju.edu.jo/Home.aspx

Obeidat, N., Ph.D., Instructor, Water and Environment Engineering, Department of Land, Water, and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *n.obeidat@ju.edu.jo*
- ORCID: 0009-0007-8481-9214
- Web of Science ResearcherID: LXA-7803-2024
- Scopus Author ID: 58952978400
- Homepage: https://agriculture.ju.edu.jo/Home.aspx

HOW TO CITE THIS ARTICLE

Hroub, H.; Rahbeh, M.; Zoubi, M.M.; Abu-Afifeh, Q.Y.; Al-Jawaldeh, H.; Obeidat, N., (2025). Projection of future temperature variations in river basins under climate change scenarios using general circulation models. Global J. Environ. Sci. Manage., 11(2): 403-426.

DOI: 10.22034/gjesm.2025.02.03

URL: https://www.gjesm.net/article_719438.html

Global J. Environ. Sci. Manage. 11(2): 427-442, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Dynamics prediction of land use changes using cellular automata and artificial neural network modeling

S.S.B. Girsang[1,*], D.M. Banurea[2], P. Lestari[3], J.B. Nambela[4], I. Verawaty[5], J. Barus[1], Jonharnas[1], M.A. Girsang[6], T. Purba[6]

[1] *Research Center for Food Crops, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor 16915, Indonesia*

[2] *Regional Research and Development Planning Agency, Pakpak Bharat Regency, Salak, 22272, Indonesia*

[3] *Research Center for Horticulture, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor 16915, Indonesia*

[4] *Research Center for Estate Crops, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor 16915, Indonesia*

[5] *Department of Agriculture, Deliserdang Regency, Lubuk Pakam, 20518, Indonesia*

[6] *Research Center for Cooperative, Corporation, and People's Economy, Research Organization for Governance, Economy, and Community Welfare, National Research and Innovation Agency, Jakarta 12710, Indonesia*

ARTICLE INFO

Article History:
Received 30 August 2024
Revised 11 November 2024
Accepted 12 January 2025

Keywords:
Environment
Land use dynamics
Leading commodities
Prediction model
Policymaker
Sustainable

ABSTRACT

BACKGROUND AND OBJECTIVES: Land use change has become one of the main issues in environmental studies and sustainable development at the global level. Although several studies have explored land use change at the regional level, an in-depth understanding of the patterns and drivers of land use change in Pakpak Bharat Regency, North Sumatra, Indonesia, is still very limited. As of now, no existing predictive model can deliver long-term perspectives on land use change trends within the region. A lack of comprehensive data and analysis can obstruct the creation of effective and sustainable spatial planning policies. Consequently, a focused study on this matter is necessary to create a pertinent scientific framework that can assist in guiding decision-making processes.

METHODS: The current study utilized spatial analysis alongside cellular automata and artificial neural network modeling techniques to project and predict land use transformations in Pakpak Bharat Regency in 2030. Geographic information system with the Molusce plugin were utilized in this study. The analysis consisted of two stages, namely land use interpretation and land use projection modeling. To ascertain the primary regional commodity, data was gathered from field studies related to soil and through interviews concerning economic factors. In contrast, secondary data on agroclimate suitability comprised altitude, air temperature data, air humidity, rainfall, wind speed, and duration of sunlight.

FINDINGS: Land uses that tended to expand were for plantations/gardens, settlement areas, and Shrubs. Meanwhile, rice fields and mixed vegetation tended to experience a reduction in area over the years. There were fluctuations in forest land use, which saw an increase in 2018 but a subsequent decrease in 2022. Furthermore, the land use prediction for 2030 in Pakpak Bharat Regency showed that land use for forests, rice fields, and Shrubs decreased. Conversely, projections indicated that the use of land for plantations, housing developments, and farming would expand. The widest durian land suitability class was quite suitable (S2), and thus, durian was recommended to be developed to maintain forests, reduce land damage, and for its high economic value.

CONCLUSION: Land use changes in the Pakpak Bharat Regency from 2014 to 2022 were relatively slow. Between 2014 and 2018, as well as from 2018 to 2022, the land use for forests experienced fluctuations, while the land use for plantations and settlements consistently rose. The 2022 land use modeling results had an excellent level of accuracy, and thus, the model could be used to predict land use in 2030. Additionally, the results revealed that durian could establish itself as the foremost regional commodity, supported by scientific evidence demonstrating its suitability for farming and profitability.

DOI: 10.22034/gjesm.2025.02.04

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
46

NUMBER OF FIGURES
7

NUMBER OF TABLES
9

*Corresponding Author:
Email: *seti011@brin.go.id*
Phone: +62813 7730 2388
ORCID: 0000 0003 2318 1273

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Population expansion affects the need for farmland, which includes agricultural use (Ariani and Susilo, 2022). This also has an impact on changes in land use in an area. Changes in land use are inevitable along with the development of human civilization. Variations in land use can result in land degradation, which may adversely influence the land's productivity and its proportional value (Tsegaye, 2019). Land use patterns that are not in accordance with land capabilities will cause various problems (Schirpke *et al.,* 2023). Therefore, understanding land use change patterns in the Pakpak Bharat Regency, Indonesia is essential in supporting sustainable spatial planning based on scientific data. Studies focused on land use play a vital role in analyzing the effects of human actions on the environment and communities, while also aiding in the creation of strategies for sustainable land use (OECD, 2020). A key goal of spatial planning and land-use management is to create environmentally sustainable, practical, and visually appealing areas, thereby improving communities' overall quality of life (Gomes *et al.,* 2024). Unlike earlier reasons for altering land use, which were predominantly shaped by socioeconomic considerations, this shift has notably affected ecosystem services (Schirpke *et al.,* 2023). Pakpak Bharat Regency is one of the regencies in North Sumatra Province, which has a hilly topography. This area is a relatively new autonomous region, resulting from the division of Dairi Regency in 2003 (Damanik and Ndona, 2022). The agricultural potential of Pakpak Bharat is significant and can be leveraged, with the expectation that this productivity will enhance the welfare of the local community, most of whom are engaged in farming (Rahmawaty *et al.*, 2020). In Pakpak Barat Regency, agriculture, forestry, and fisheries are the primary contributors to the gross regional domestic product (GRDP), representing 80.32 percent (%) of the overall GRDP (BPS, 2024). Hariyanti *et al.* (2024) stated that leading commodities are essential products that hold significant potential for regional growth. Their plantation location is affected by multiple factors, including technical elements (like soil and climate conditions) as well as socioeconomic and institutional factors (such as technological knowledge, workforce skills, infrastructure, and local sociocultural aspects). Key commodities specific to each region are essential for boosting the community's economy through the efficient and sustainable management of regional resources. Pakpak Bharat Regency has an area of 121,830 hectares (ha) (BPS, 2024), with an economic focus on agriculture, especially plantation sub-sectors. In the Gayo Highlands of Aceh Province, which has a landscape similar to Pakpak Bharat, there has been a reduction in forested areas and rice fields, along with a rise in the extent of agricultural fields, housing, plantations, and unused land from 2013 to 2022. It is vital to encourage sustainable agricultural practices in the forest areas adjacent to Bener Meriah Regency and Central Aceh Regency to ensure their long-term sustainability (Arico *et al.,* 2023; Anhar *et al.*, 2024). In another study in Balik Bukit Regency, West Lampung Regency, it was found that the settlement distribution pattern showed a clustered pattern. Meanwhile, the topographic factors that are the benchmarks for the formation of settlement distribution patterns are slope and elevation. In this area, the higher the altitude, the more clustered the settlement pattern was in certain areas, ranging from 400-1,400 m (asl). Analyzing the slope reveals two primary settlement patterns: a clustered arrangement on slopes between 0% and 45%, and a more spread-out configuration on slopes greater than 45% (Sari *et al.*, 2024). Land use is always in a state of flux, evolving continuously due to the dynamic interactions between various drivers and the feedback that results from land use changes affecting these drivers (Lambin *et al.,* 2003). Understanding the dynamics of these changes is vital to designing policies that support sustainable natural resource management. One crucial approach in land use change research is identifying and analyzing the driving factors contributing to these changes (Zhang *et al.,* 2024). Examining the underlying driving factors reveals the mechanisms that contribute to land use change and assists in anticipating future developments (Xiao *et al.,* 2022). Therefore, focusing on the driving factors is critical in supporting data-driven decision-making for sustainable land management (Fida *et al.,* 2024). According to Kim *et al*. (2020), the driving factors are divided into natural, built-up land, and socioeconomic factors. The driving factors used in this study encompassed these three factors, such as distance to rivers and slopes, distance to roads, and population density. This study sought to analyze the evolution of land use in Pakpak Bharat Regency during designated periods and to project future land use scenarios. Analyzing land use change through spatial

data is increasingly prevalent in various research, as it is particularly beneficial for tracking areas undergoing alterations by focusing on visual characteristics and calculating the expansion and contraction of land areas (Zhao *et al.,* 2021). The use of Geographic Information Systems (GIS) allows for the assessment of land use change modeling across designated time periods (Bielecka, 2020; Abousaeidi *et al.*, 2015). The selection of land use change modeling approaches often hinges on practical factors rather than theoretical ones (Hersperger *et al.,* 2010; Puno and Puno, 2019). In this study, the cellular automata-artificial neural network (CA-ANN) model was applied to forecast and anticipate changes in land use in 2030 within the Pakpak Bharat Regency.

MATERIALS AND METHODS

Study area

The study was conducted in Pakpak Bharat Regency from April to October 2024. Pakpak Barat Regency is located in North Sumatra Province, Indonesia. Geographically, Pakpak Bharat is on 2°15'-3°32' north (N) latitude and 96°00'–98°31' east (E) longitude. The total area of Pakpak Bharat regency is 1,218.30 square kilometers (km^2), consisting of eight sub districts: Salak, Kerajaan, Sitellu Tali Urang Jehe, Tinada, Siempat Rube, Sitellu Tali Urang Julu, Pergetteng Getteng Sengkut, and Pagindar. The geographic location of the study area is presented in Fig. 1.

The collected information comprises rectified land

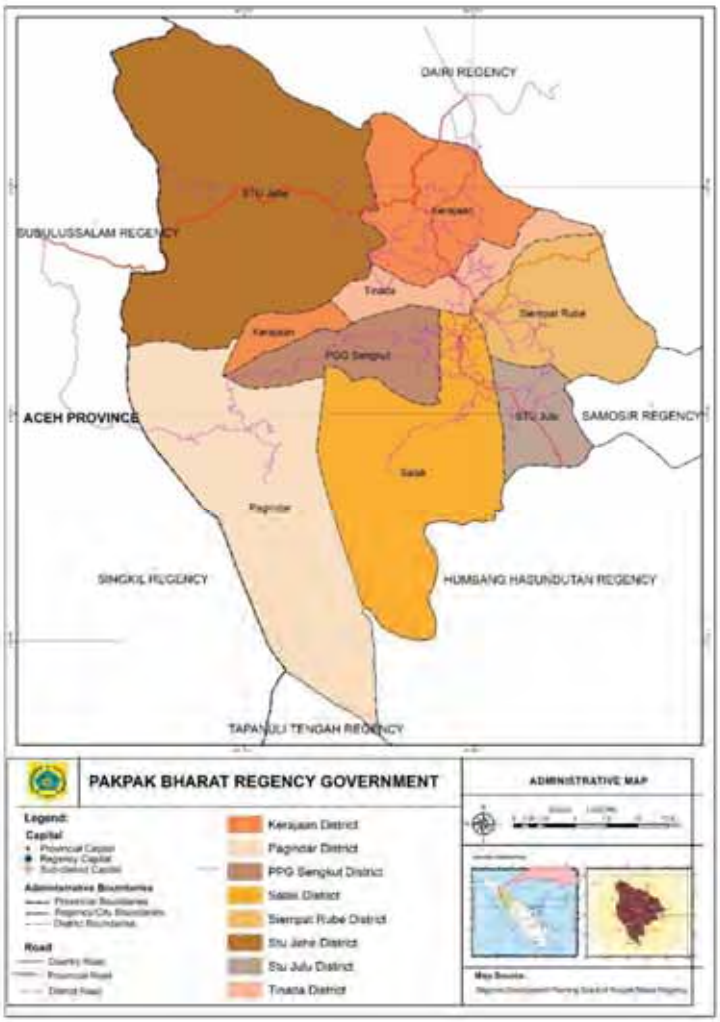


Fig. 1: Geographic location of the study area in Pakpak Bharat Regency, North Sumatra, Indonesia

imagery from 2014, 2018, and 2022, an administrative map of Pakpak Bharat Regency, Soil map, Indonesia's topographical map (RBI), population density data, Shuttle Radar Topography Mission-Digital elevation model (SRTM-DEM) data, forest area status maps from the Ministry of Environment and Forestry, land use maps from the National Land Agency, land ownership maps from the Ministry of Agrarian Affairs and Spatial Planning, and land suitability criteria for agricultural commodities. The data was processed and analyzed using a computer that featured an Arc geographic information system map alongside a quantum geographic information system (QGIS), enhanced by the Molusce plugin.

Land use interpretation

Land use interpretation is carried out by visual interpretation. Understanding visual images involves recognizing the characteristics of spatial objects by employing nine essential interpretation keys, namely hue and color, shape, size, texture, pattern, shadow, site, and association. The results of the visual interpretation produce land use maps for 2014, 2018, and 2022. The identified land use classifications consist of forests, plantations, settlements and activity sites, rice fields, Shrubs, rivers, and mixed vegetation. This interpretation is performed utilizing Arc Map software.

Land use projection modeling

Land use projection modeling is carried out using the Molusce plugin in QGIS software. Molusce is one of the plugins used to analyze, model, and simulate land use using utility algorithms such as artificial neural networks (ANN), multi-criteria evaluation (MCE), weights of evidence (WoE), logistic regression (LR), Monte Carlo cellular automata (MCA) models (Black *et al.,* 2023; Wu *et al.*, 2021). In the modeling process, raster data was utilized, necessitating a conversion of the map format from vector to raster. A pixel size of 30 by 30 meters (m) was used for this analysis. The 2014 land use map served as the starting year data (t0), while the 2018 land use map served as the ending year (t1). The changes in land recorded between 2014 and 2018 were classified as dependent variables in the model, and the land use map derived from 2022 was utilized to validate the projected modeling map. The simulation forecasted the spatial-temporal potential for 2022 by employing the ANN algorithm approach along with cellular automata modeling (Pingel, 2018; Gharaibeh, 2020). The independent variables employed in the modeling process comprised distances derived from road maps, maps illustrating the proximity to water sources such as rivers, population density maps, and slope gradient maps. The road and river maps were sourced from Indonesia's topographical map maps at a scale of 1:50,000. Distance maps of roads and rivers were generated using Euclidean distance methods in Arc Map, which measured the distance between objects. Additionally, population density data was employed to generate a population density map corresponding to each pixel. The slope map was developed using SRTM-DEM. Using this data, projections for land use in the Pakpak Bharat Regency in 2030 were made. Furthermore, a precise analysis of the modeling outcomes was carried out to determine the dependability of the projected land use changes. The Kappa statistical test was performed with the assistance of an error matrix, using Eqs. 1 to 3 (Li, 2010):

$$\text{Kappa} = P(A/(1\text{-}PE) \quad (1)$$

$$\text{Kappa Loc} = P(A\text{-}PE)/P_{max}\text{-}P(E) \quad (2)$$

$$\text{Kappa Histo} = Pmax\text{-}P(E)/1\text{-}P(E) \quad (3)$$

Based on the calculation of Eq. 1, the Kappa test results are classified into several classes, as shown in Table 1. It shows the accuracy of land use predictions into several categories ranging from low to high.

Table 1: Interpretation of Cohen's Kappa (Kunz, 2017)

Kappa coefficient value	Interpretation of Kappa value
<0.2	Poor
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Good
> 0.80	Very good

Land suitability for leading regional commodities

The land suitability and key commodities map was developed at a scale of 1:50,000. The evaluation of land suitability involved a manual process that considered soil characteristics, climate, and topography, adhering to the criteria set for assessing land suitability for agricultural commodities (Djaenudin *et al.,* 2003). Existing land and area status were considered in determining the leading regional commodities. The approach used was descriptive with quantitative and qualitative methods.

RESULTS AND DISCUSSION

Land use interpretation

The identified land cover classes referred to the results of field checks and land cover classifications issued by the Pakpak Bharat Regency Government. An analysis of visual imagery revealed seven categories of land use within Pakpak Bharat Regency, i.e., forests, plantations, settlements and activity places, rice fields, Shrubs, rivers, and mixed vegetation.

Additionally, the classification of each land segment relied on groups of pixels that exhibited similarities in color, hue, and other interpretative characteristics. Based on the interpretation results, land use in the regency was dominated by forests, accounting for more than 77% of the total area. Visual interpretation at three observation year points (2014, 2018, and 2022) showed that there were changes in land use from year to year, although the changes were relatively small. In Ghana, a similar case was observed, with an annual deforestation rate of just 0.06%. This figure emphasizes the positive influence of long-term forest area protection programs (Dembélé *et al.*, 2024). The land use map originating from satellite image interpretation is presented in Fig. 2, while the

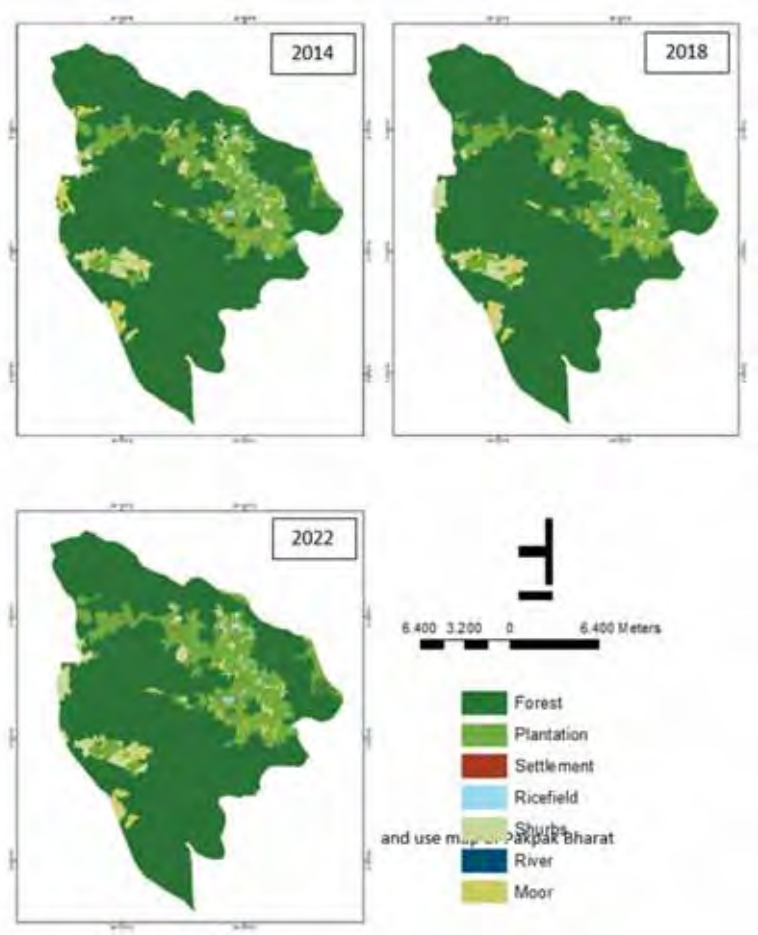


Fig. 2: The 2014, 2018, and 2022 land use map of Pakpak Bharat

Table 2: Land use area in 2014, 2018 and 2022

Land use type	2014		2018		2022	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Forest	105,329.30	77.67	105,372.49	77.70	104,488.45	77.05
Plantation	19,736.31	14.55	20,548.79	15.15	21,498.25	15.85
Settlement	320.99	0.24	329.30	0.24	359.52	0.27
Rice field	1,389.63	1.02	1,312.79	0.97	1,305.30	0.96
Shrubs	6,131.89	4.52	6,175.29	4.55	6,196.17	4.57
River	119.21	0.09	119.21	0.09	119.21	0.09
Mixed vegetation	2,579.76	1.90	1,749.21	1.29	1,640.19	1.21
Total	135,607.08	100.00	135,607.08	100.00	135,607.08	100.00

Table 3. Land use change matrix in Pakpak Bharat Regency 2014 – 2018

Land use in 2014	Land use in 2018							Total
	1	2	3	4	5	6	7	
1	103,978.28	-	-	-	1,009.43	-	384.78	105,372.49
2	251.34	19,574.22	-	86.68	636.55	-	-	20,548.79
3	-	3.33	320.99	2.29	-	-	2.69	329.30
4	-	9.19	-	1,300.66	2.95	-	-	1,312.79
5	864.79	149.57			4,419.82		741.11	6,175.29
6	-	-	-	-	-	119.21	-	119.21
7	234.89	-	-	-	63.14	-	1,451.18	1.749,21
Total	105,329.30	19,736.31	320.99	1,389.63	6,131.89	119.21	2,579.76	135,607.08

Note: 1. Forest, 2. Plantation, 3. Settlement, 4. Rice field, 5. Shrubs, 6. River, 7. Mixed vegetation

area of change is shown in Table 2.

According to Table 2, the shifts in land use in Pakpak Bharat appear to occur at a slow pace. The regency area is far from Medan, the government center in North Sumatra Province. Other regencies in North Sumatra Province are directly adjacent to Medan such as Deli Serdang. According to Verawaty *et al.* (2023), the rate at which land use changes in the Deli Serdang Regency is significant. The area's strategic positioning adjacent to Medan greatly influences its dynamics. Furthermore, the distance from land to transportation routes and the capitals of districts or provinces is a key factor in the transformation of land use (Siagian *et al.*, 2019)**.** Land uses that tended to increase in the area were plantations, settlements and activity areas, and Shrubs. Over the years, there has been a noticeable decline in the area covered by rice fields and mixed vegetation. Forest land use tended to fluctuate as it increased in 2018 but decreased in 2022. This is related to Pakpak Bharat Regency's support of the national program to achieve national food security, which is anticipatory step in facing the world food crisis. The Pakpak Bharat Regency Government has promulgated Pakpak Bharat Regent Regulation Number 29 of 2022 which exempts regional asset utilization levies for land cultivation as part of its initiative to develop food estate. The matrix of changes in each land is shown in Tables 2 and 3. Table 3 presents the matrix illustrating land use alterations and the areas affected during the observation interval of 2014 to 2018. During this period, there was a change from forest to Shrubs of 1,009.43 ha and mixed vegetation of 384.78 ha. Deforestation, characterized by the decrease in forest cover, can lead to a shift from forest ecosystems to shrub land. The Land use changes in Pakpak Bharat reflect patterns in other Indonesian regions and globally. A significant similarity observed in Indonesia include; 1) Deforestation for plantations, as in the Gayo Highlands, driven by high-value crops like coffee, palm oil, and durian (Anhar *et al.*, 2024); 2) Urbanization and settlement expansion, though slower in Pakpak Bharat, aligning with trends in areas like Deli Serdang (Siagian *et al.*, 2019); and 3) The transition in agricultural practices, where rice fields and various lands are repurposed for plantations and infrastructure initiatives, underscores the current socioeconomic priorities (Schirpke *et al.*, 2023). Globally, Pakpak Bharat parallels; 1) Tropical forest dynamics, with cycles of deforestation and regrowth

observed in the Amazon and Southeast Asia (Cheng *et al.,* 2024); 2) Slow changes in remote areas, where difficult access results in gradual land-use transition (Long *et al.*, 2021).

Shrubs found in areas that were formerly forested can serve as indicators that the land was once characterized by mixed vegetation or had been subjected to logging or other industrial activities, such as mining. On the other hand, changes from Shrubs to forests also had a fairly large area, reaching 864.79 ha. The process is a natural process of forest succession or, in other words, returning to its original condition. Moreover, a considerable transformation took place in land use, transitioning from Shrubs to mixed vegetation, encompassing 741.11 ha. Changing Shrubs into mixed vegetation has positive impacts, such as increasing agricultural activities, farmers' incomes, and the regional economy. The incorporation of diverse plant species within a region provides numerous benefits and contributes to the enhancement of biodiversity and ecosystem services (Brockerhoff *et al.,* 2017). The significant change in the observation period from 2018 to 2022 was the change from forest to plantation and Shrubs (Table 4).

Between 2018 and 2022, a remarkable transformation occurred, marked by the shift from forest ecosystems to areas dominated by plantation and shrub areas. The conversion from forest to plantation reached 650.20 ha, while the change from forest to Shrubs amounted to 701.77 ha. Land is often transformed from plantations during the expansion of plantation regions. This is supported by the potential area of Pakpak Regency, which boasts leading commodities like plantation crops, including coffee, gambir, frankincense, and durian. Conversely, the change in land use from shrubs to plantations was markedly evident, encompassing an area of 436.70 ha. This shift is indicative of initiatives aimed at expanding or developing primary plantation products.

Land use change modeling

The process of land use change modeling involves several critical stages, which include the evaluation of correlations, examination of area changes, modeling of transition potential, simulation using cellular automata, and subsequent validation.

Evaluating correlation

The statistical correlation test was carried out using Pearson's correlation method on all existing driving factors on the variables of population density, distance to water sources, slope, and distance to roads. Pearson's Correlation serves as a statistical measure that evaluates the linear relationship and dependence between two variables, typically denoted as X and Y (Zhou *et al.,* 2016). The higher the correlation number, the greater the influence between the variables. Pearson's correlation has a value range of -1 to 1, with a positive value (+) indicating a + relationship (if A increases then B increases), while a value (-) indicates an inverse relationship. The findings from the correlation test regarding the factors driving land use change are illustrated in Table 5.

As shown in Table 5, the correlation coefficient of 0.20519 reflects the relationship between the road network and the distribution of population density in the Pakpak Bharat Regency, indicating a degree of correlation and dependency between these variables. The shorter the distance to the road, the greater the population density. **T**he accessibility of road networks is positively associated with the

Table 4. Land use change matrix in Pakpak Bharat Regency 2018 – 2022

Land use in 2014	Land use in 2022							Total
	1	2	3	4	5	6	7	
1	103,976.77	650.20	-	4.98	701.77	-	38.76	105,372.49
2	38.76	20,398.38	19.45	-	92.31	-	-	20,548.79
3	-	-	329.30	-	-	-	-	329.30
4	-	3.30	9.18	1,300.31	-	-	-	1,312.79
5	356.35	436.70	-	-	5,287.67	-	94.57	6,175.29
6	-	-	-	-	-	119.21	-	119.21
7	116.57	9.78	1.58	-	114.42	-	1,506.86	1,749.21
Total	104,488.45	21,498.25	359.52	1,305.30	6,196.17	119.21	1,640.19	135,607.08

Note: 1. Forest, 2. Plantation, 3. Settlement, 4. Rice field, 5. Shrubs, 6. River, 7. Mix Vegetation

Table 5: Correlation test between factors driving land use change

Driving factor	Population density	Distance to river	Slope	Distance to road
Population density	---	-0.04665	0.09641	0.20519
Distance to river	---	---	0.19040	0.04980
Slope	---	---	---	0.31892
Distance to road	---	---	---	---

Table 6: Transition probability land use change transition matrix

Land use	1	2	3	4	5	6	7
1	0.98717	0.00239	0	0	0.00821	0	0.00222
2	0	0.99186	0.00016	0.00049	0.00749	0	0
3	0	0	1	0	0	0	0
4	0	0.06263	0.00156	0.93582	0	0	0
5	0.16426	0.10382	0	0.00039	0.72119	0	0.01032
6	0	0	0	0	0	1	0
7	0.14911	0	0.00098	0	0.28719	0	0.56273

Description: 1. Forest, 2. Plantation, 3. Settlement, 4. Rice field, 5. Shrubs, 6. River, 7. Mixed vegetation

population density (Shi *et al.*, 2024). A study by Tang *et al.* (2023) showed that road construction in an area had an effect on reducing forest and wetland boundaries due to increasing population density**.** In contrast, the inverse relationship observed between population density and distance from water sources implies that as individuals move nearer to the water source, such as the river, the population density diminishes. Additionally, the positive correlation between the slope factor and the distance to the road further highlights the dependency relationship.

Area change

The transition probability matrix indicates the extent of potential land use changes. The values in this matrix range from 0 to 1. When a value is between 0.01 and 0.99, it denotes a possibility of change in land use. Conversely, values of 0 and 1 indicate that land use is either unchanged or likely to remain so (Rakuasa *et al.*, 2023). The transition matrix of land use changes in Pakpak Bharat Regency, as analyzed by Molusce, is shown in Table 6. The diagonal component of the matrix of residential land use and activity sites and river land use has the largest value maximum 1 (Table 6) which explains that the use of the land tends not to change or remains the same. The value of the coefficient for the shift from mixed vegetation to shrubs is significantly large, standing at 0.28719. This indicates that there is a greater opportunity for this particular change compared to the possibilities of converting to forests or other types of land use. According to Kodero *et al.* (2024), the forest conversion to shrubs on the environment results in the loss of carbon storage of up to -82 gigagrams (Gg). Likewise, shrub land exhibits a greater capacity for transformation into forest (0.16426) than for shifting to alternative land uses.

Transition potential modeling

The network topology used is multi layer perception (MLP) with 10 nodes in the hidden layer. Every node in the layer will interact with other nodes, indicating a relationship or connection path marked by (W) as the weight in the matrix. The modeling results can be seen in Table 7.

The analysis revealed an error value of 0.01401, where a decrease in the error value corresponds to enhanced performance of the developed model. Grekousis (2019) stated that the ANN-CA model had better performance in 75.7% of case studies compared to conventional methods. Moreover, the ANN-CA model produces reliable predictions for future land use and land cover (LULC) (Saputra and Lee, 2019). The optimal performance outcome mirrored the momentum results of 0.050, as it is instrumental in assessing the weight associated with a prediction. A range of parameters that can affect and differentiate the outcomes of land use change predictions encompass the iteration value, momentum value, or even pixel cell size in the initial

modeling data. The curve results from ANN modeling are shown in Fig. 3.

Cellular automata

The cellular automata phase generated forecasts of land use modifications for 2022, utilizing land use data from 2014 and 2018. In Fig. 4, a comparison is made between the outcomes of land use modeling for 2022 and the actual land use map for the same year within the Pakpak Bharat Regency. Furthermore, Table 8 presents a breakdown of the area designated for each land use category. Evidently, there was no significant difference in the area of each land use category.

Validation of the predictive model referenced earlier was conducted through supplementary analysis that employed statistical methods, specifically a Kappa accuracy test. The results from the Kappa accuracy test on the anticipated land use changes in Pakpak Bharat Regency for 2022 compared to the current land use in the same year yielded a Kappa value of 0.94600, reflecting a correctness rate of 97.97%. This accuracy metric serves as a dependable indicator of prediction outcomes and is utilized as a benchmark for developing future policy frameworks. According to Saputra and Lee (2019), correctness percentage of 87.28% with a Kappa index of 0.83 illustrated the high agreement between predicted and real LULC maps. Of course, it is necessary to review the prediction results with physical conditions in the field to create appropriate policies. When evaluating sustainable food agriculture land (LP2B), it becomes clear that despite the promising predictions and actual data regarding rice fields, the likelihood of land conversion increases if the area is situated near roads and residential developments. Therefore, the determination of the LP2B location is shifted to a more suitable area. Furthermore, the validation results are presented in Fig. 5. The Kappa value showed that the modeling fitted well (Xiao *et al.,* 2022) since the value was in a category of > 0.80.

Table 7: Transition potential modeling

Method: ANN	Value
Neighborhood	1
Learning rate	0.1
Maximum iterations	1000
Hidden layers	10
Momentum	0.05
Overall accuracy	-0.00141
Min validation overall error	0.01401
Current validation Kappa	0.87732

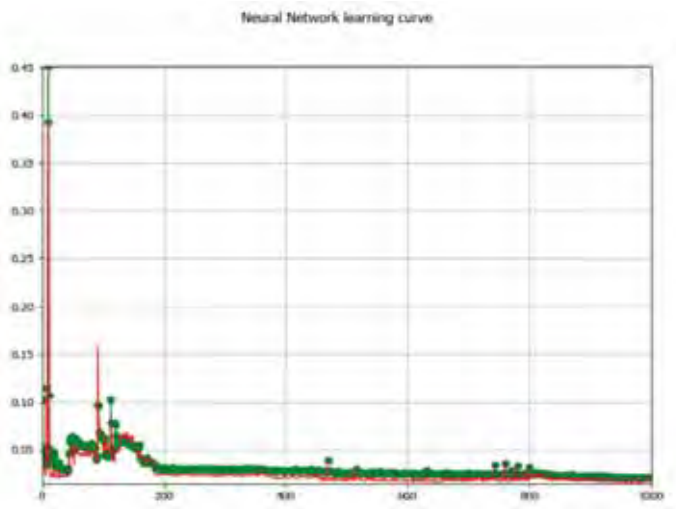


Fig. 3: ANN modeling curve

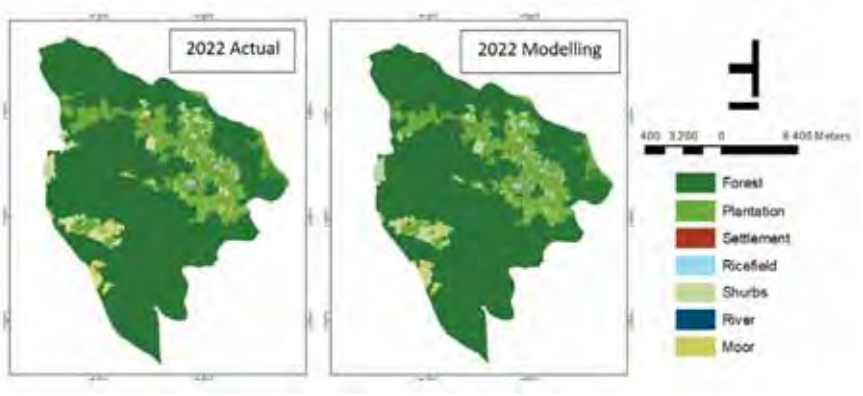


Fig. 4: Modeling map 2022 (A) and Actual land use map 2022 (B)

Table 8: Comparison between modeling and actual land use area in 2022

Land use	Modeling (ha)	Actual land use area (ha)
Forest	105,434.13	104,488.45
Plantation	20,579.58	21,498.34
Settlements	319	359.52
Rice fields	1,282.68	1,305.30
Shrubs	6,132.29	6,196.26
River	112.24	119.21
Mixed vegetation	1,747.13	1,640.19

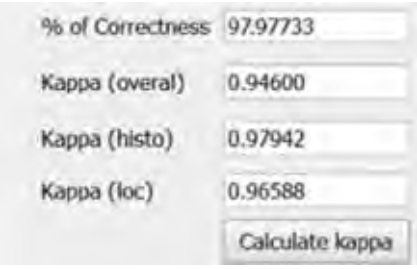


Fig. 5: Validation of the 2030 land use prediction model

The analysis of land use for 2022 revealed a significant Kappa value, underscoring the model's capability to accurately predict land use in 2030. The anticipated land use outcomes for Pakpak Bharat Regency in 2030 are illustrated in Fig. 6. As indicated in Table 8, the expected changes in land use distribution for Pakpak Bharat Regency in 2030 are detailed in Table 9. The findings in Table 9 reveal a decline in the areas assigned to forests, rice fields, and shrubs for that year. On the other hand, the land used for plantations, settlements, and mixed vegetation increased. This trend occurs based on the dynamic pattern of changes that happened in the previous years. Although there was a decline, land use for forests still had the highest percentage, reaching 76.99%. In order to sustain the forest and lessen erosion from steep inclines, it is suggested to cultivate plantations in the Pakpak Bharat Regency, with plans for area expansion by 2030.

Potential commodities for regional leading commodities

Based on the 1:50,000 scale land suitability map (Fig. 7), durian commodity obtains an S2 suitability class (moderately suitable) for soil and agroclimate and is economically profitable. Moderately suitable

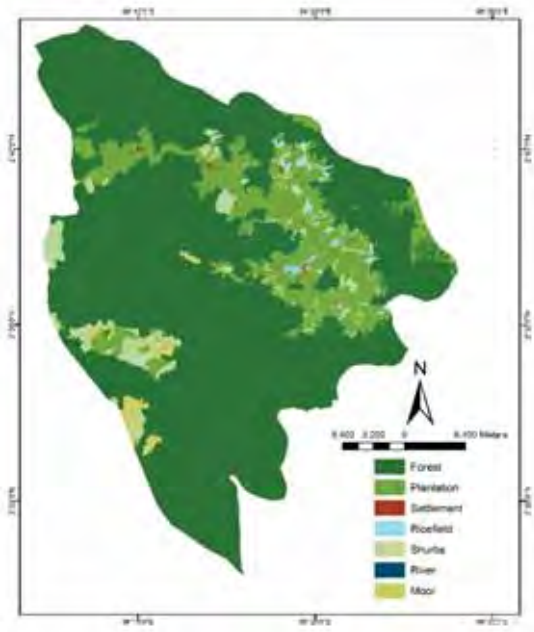


Fig. 6: Land use prediction map of Pakpak Bharat Regency 2030

Table 9: Gap area in land use area 2022 – 2030

Land use	Existing in 2022 (ha)	Prediction for 2030 (ha)	Gap area (ha)
Forest	104,488.45	104,398.19	-90.26
Plantation	21,498.25	21,567.02	68.77
Settlement	359.52	369.39	9.87
Rice field	1,305.30	1,275.18	-30.12
Shrubs	6,196.17	6,131.89	-64.28
River	119.21	119.21	-
Mixed vegetation	1,640.19	1,746.21	106.02

land (S2) for durian was 1.12%, and marginally suitable land (S3) covered 64.03% of the regency area. Unsuitable land (N) covered 34.50%, and other land uses were 0.35%. Siempat Rube Subdistrict was found to have the most extensive moderately suitable land for durian, totaling 963.42 ha. It was succeeded by Sitellu Tali Urang Jehe at 569.15 ha, Kerajaan at 374.59 ha, and the least suitable area in Tinada, which spans 176.25 ha. Based on climate, durian commodity is categorized as S2 (moderately suitable land). Furthermore, evaluation results showed that moderately suitable land (S2) was limited by low cation exchange capacity (CEC, nr1) and base saturation (BS, nr2). Meanwhile, marginally suitable land (S3) for durian was constrained by slightly coarse texture (rc2), very low base saturation (nr2), deficient organic carbon (nr4), and steep slopes (Eh1). Besides the aforementioned limiting factors, the marginally suitable land (S3) was hindered by slightly coarse soil texture (rc2). Enhancing soil with organic matter can counteract the negative consequences of its texture. Jiang *et al.* (2022) reported that organic fertilizers influenced soil aggregate stability, plant biomass, and production. It is advisable to implement terrace construction as a measure to mitigate erosion. According to Rutebuka *et al.* (2021), terraces can reduce erosion and support soil fertility. Furthermore, Fernandes and Gontijo (2020) found that Vegetated terraces could reduce erosion while encouraging pest control. The gap in land use area in 2030 compared to the existing conditions in 2022 (Table 9) showed an addition of 68.77 ha of plantation area, which could be used for planting durian in S2-class areas. Likewise, despite the anticipated reduction of forest areas by

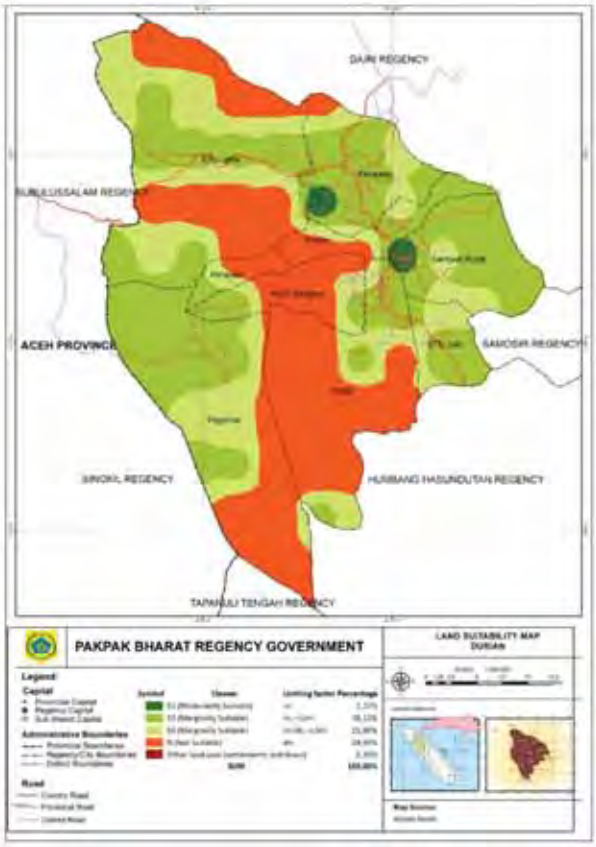


Fig. 7: Land suitability map for durian commodity in Pakpak Bharat Regency (scale 1:50,000)

90.26 ha by 2030, it is crucial to identify and establish durian cultivation within production forests situated in S2-class regions. Another favorable point is that durian cultivation is lucrative, boasting a return-to-cost ratio (R/C) of 1.99. This value is indeed lower than durian cultivation in Parigi Moutong Regency, which had an R/C value of 3.52 (Parniati *et al.*, 2022). The low R/C value can be explained by the classification of durian as a forest plant, which is characterized by its low input requirements. However, to date, there are approximately 63,774 durian tree populations in Pakpak Bharat Regency, with 92 farming households cultivating them (BPS, 2024). Therefore, developing a leading regional commodity, namely durian in Pakpak Bharat Regency, is recommended by establishing durian plantation areas and increasing farmer capacity in cultivation, post-harvest, and exports.

CONCLUSION

The study offers an in-depth insight into the dynamics of land use changes in Pakpak Bharat Regency from 2014 to 2022. Throughout this time frame, the modifications in land use happen at a gradual rate, echoing the region's characteristics, which are mainly marked by natural land uses like forests, along with human activities that are primarily concentrated in particular sectors. One of the study's significant findings is the fluctuation in the use of forests in the two analysis periods, namely 2014–2018 and 2018–2022. The variations suggest that the interactions within the forest ecosystem are shaped by human activities, including land conversion for economic activities as well as the potential for natural processes like forest regrowth. The variability may also indicate that forest management policies are still in a state of development and lack long-term stability or consistency. The modeling results to predict land use in 2022 show excellent accuracy. The high accuracy of the model provides confidence that the model used can represent the dynamics of land change well based on the parameters and variables analyzed. Therefore, the model is considered suitable for projecting future

land use patterns, including for 2030. In the policy context, the study results significantly contribute to spatial management in the Pakpak Bharat Regency. Local governments can use the study results to develop more effective and sustainable land management strategies. Additionally, projections regarding land use in 2030 can guide the government in establishing key priorities for infrastructure projects and resource allocation, enabling the optimization of regional capabilities while maintaining a focus on sustainability. The study identifies durian as the potential leading regional commodity due to the S2 (moderately suitable) classification for both soil and agroclimatic conditions and its economic viability. Even though land use change in Pakpak Bharat Regency occurs at a slow rate, it is important to identify the patterns of transformation that should be taken into account for effective sustainable spatial planning management. By leveraging the results from the analysis and prediction made, local authorities will be able to create policies that meet the development requirements while preserving environmental sustainability for future generations and enhancing societal well-being.

AUTHOR CONTRIBUTIONS

S.S.B. Girsang performed the conceptualization and design, statistical analysis, obtaining funding, and supervision. J.B. Nambela performed on acquisition of data and drafting of the manuscript. I. Verawaty performed on analysis and interpretation of data, drafting of the manuscript, and statistical analysis. P. Lestari performed on acquisition of data, drafting of the manuscript, and critical revision of the manuscript for important intellectual content. J. Barus on acquisition of data, drafting of the manuscript, and critical revision of the manuscript for important intellectual content. D.M. Banurea performed data collection, a literature review, and obtaining funding. Jonharnas performed data collection and a literature review. M.A. Girsang performed data collection and a literature review. T. Purba performed some remained experiments.

ACKNOWLEDGEMENT

The experiment was conducted in Pakpak Bharat, North Sumatra Indonesia by the National Research and Innovation Agency (BRIN) and the Pakpak Bharat Regional Government team. The authors thank Harryson F. Sirumapea, Roy Efraim Bancin, Yudhistira Nugraha, Andari Risliawati for for management, the formation of the BRIN and Pakpak Bharat collaboration. Authors also thank Karunia Alkoda Ronal Bancin, Paingot Sinamo, Dorkas Parhusip, Amelia Sebayang, and Shabil Hidayat, and all extension workers for the management of administration and field research. This manuscript is funded through self-managed cooperation between the Pakpak Bharat Regional Government and Indonesia National Research and Innovation Agency number [24/III.11/HK/2024].

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of the manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims with regard to published maps and institutional affiliations.

ABBREVIATIONS

%	Percent
ANN	Artificial neural network
Asl	Above sea level

Bmkg	Badan Meteorologi Klimatologi dan Geofisika (Meteorological, Climatological and Geophysical Agency of Indonesia)
Bps	Badan Pusat Statistik (Central Bureau of Statistics of Indonesia)
Brin	Badan Riset dan Inovasi Nasional (The National Research and Innovation Agency of Indonesia)
BS	Base Saturation
CEC	Cation exchange capacity
Dem	Digital elevation model
E	East
Eh1	Slope
Gdrp	Gross regional domestic product
Gg	Gigagram
GIS	Geographic Information System
ha	Hectare
Km²	Square kilometer
Lr	Logistic regression
LULC	land use and land cover
M	Meters
MCA	Monte carlo cellular automata
MCAE	Multi-criteria evaluation
N	North
N	Not suitable (Land suitability classification)
Nr1	Cation exchange capacity
Nr2	Base saturation
Nr4	Carbon organic
OECD	Organization for Economic Co-operation and Development
QGIS	quantum geographic information system
Rbi	Rupabumi Indonesia (Topography of Indonesia)
Rc2	Texture
R/C	Revenue cost ratio
Srtm	Shuttle radar topography mission
S1	Very suitable (Land suitability classification)
S2	Moderately suitable (Land suitability classification)
S3	Marginally suitable (Land suitability classification)
WoE	Weights of evidence

REFERENCES

Abousaeidi, M.; Fauzi, R.; Muhamad, R., (2015). Geographic information system (GIS) modeling approach to determine the fastest delivery routes. Saudi J. Biol. Sci., 23: 10.1016 **(10 pages).**

Anhar, A.; Muslih, A.M.; Baihaqi, A.; Abubakar, Y., (2024). Changes in land use and land cover in forest areas in Bener Meriah and Aceh Tengah Districts, Indonesia. IOP Conference Series: Earth Environ. Sci., 1297: 012085 **(10 pages).**

Arico, Z.; Rahmawaty; Delvian; Harahap, H.; Ismail, M.H., (2023). Analysis of land use (2013-2022) in the Gayo highlands, Aceh, Indonesia. Global Forest J., 1(1): 27-32 **(6 pages).**

Ariani, R.D.; Susilo, B., (2022). Population pressure on agricultural land due to land conversion in the suburbs of Yogyakarta. IOP Conference Series: Earth Environ. Sci., 1039: 012039 **(10 pages).**

Bielecka, E., (2020). GIS spatial analysis modeling for land use change. A bibliometric analysis of the intellectual base and trends. Geosciences. 10: 421 **(21 pages).**

Black, B.; Van Strien, M.J.; Adde, A.; Grêt-Regamey, A., (2023). Re-considering the status quo: Improving calibration of land use change models through validation of transition potential predictions. Environ. Model. Software. 159: 105574 **(10 pages).**

BPS, (2024). Pakpak Bharat regency in figures 2024. 21 BPS-Statistics Pakpak Bharat Regency. in Bahasa Indonesia **(494 pages).**

Brockerhoff, E.G.; Barbaro, L.; Castagneyrol, B.; Forrester, D.I.; Gardiner, B.; Gonza'lez-Olabarria, J.R.; Lyver, P.O.B.; Meurisse, N.; Oxbrough, A.; Taki, H.; Thompson, I.D.; Plas, F.v.d.; Jactel, H., (2017). Forest biodiversity, ecosystem functioning and the provision of ecosystem services. *Biodivers Conserv* **26**, 3005–3035 (2017) **(31 pages)**

Cheng, Z.; Wu, J.; Luo, C.; Liu, Z.; Huang, E.; Zhao,H.; Dai, L.; Weng, C., (2024). Southeast Asian rainforest lost biodiversity during the range expansion to ice-age Sunda Shelf, Global and Planetary Change, Vol. 242, 104597 **(8 pages)**

Damanik, E.L; Ndona, Y., (2022). Alignment: Conflict resolution through sulang-silima among pakpaknese, Indonesia. Asian J. Soc. Sci., 50(2): 96-103 **(8 pages).**

Dembélé, F.; Guuroh, R.T.; Ansah, P.B.; Asare,D.C.B.M.; Da, S.S.; Aryee, J.N.A.; Bredu, S.A., (2024). Land use land cover change and intensity analysis of land transformation in and around a moist semi-deciduous forest in Ghana, Trees, Forests and People, Vol. 15, 100507 **(14 pages).**

Djaennudin, D.; Marwan H.; Subagjo H.; dan Hidayat. A., 2003. Technical guidelines for land evaluation for agricultural commodities. Soil Research Center, Bogor, Bahasa Indonesia. **(154 pages).**

Fernandes, A.C.S.A.; Gontijo, L.M., (2020). Terracing field slopes can concurrently mitigate soil erosion and promote sustainable pest management, J. Environ. Manage., 269: 110801 **(7 pages).**

Fida, G.T.; Baatuuwie, B.N.; Issifu, H., (2024). Dynamics of land use/cover change and its drivers during 1992–2022 in Yayo coffee forest biosphere reserve, Southwestern Ethiopia. Sustainable Environ., 10(1): 2374119: 1-21 **(21 pages).**

Grekousis, G., (2019). Artificial neural networks and deep learning in urban geography: A systematic review and meta-analysis, Computers, Environment and Urban Systems, Vol. 74, **(pages 13)**.

Gharaibeh, A.; Shaamala, A.; Obeidat, R.; Al-Kofahi, S., (2020). Improving land-use change modeling by integrating ANN with cellular automata-markov chain model. Heliyon. 6(9): e05092 **(18 pages).**

Gomes, E.; Costa, E.M.d.; Abrantes, P., (2024). Spatial planning and land-use management. Land. 13: 94 **(6 pages).**

Hariyanti, F.; Syahza, A.; Zulkarnain; Nofrizal., (2024). Economic transformation based on leading commodities through sustainable development of the oil palm industry. Heliyon. 10(4): e25674 **(17 pages)**.

Hersperger, A. M.; Gennaio, M.; Verburg, P.H; Bürgi, M., (2010). Linking land change with driving forces and actors: four conceptual models. Ecol. Soc., 15(4): 1 **(17 pages).**

Jiang, Y.; Zhang, J.; Manuel, D-B.; Beeck, M.O.d.; Shahbaz, M.; Chen, Y.; Deng, X.; Xu, Z.; Li, J.; Liu, Z., (2022). Rotation cropping and organic

fertilizer jointly promote soil health and crop production. J. Environ. Manage., 315: 115190 **(11 pages).**

Kodero, J.M.; Felzer, B.S.; and Shi, Y., (2024). Future transition from forests to shrublands and grasslands in the western United States is expected to reduce carbon storage. *Commun Earth Environ* **5**, 78 **(10 pages)**.

Kim, Y.; Newman, G.; Güneralp, B., (2020). A review of driving factors, scenarios, and topics in urban land change models. Land. 9: 246 **(22 pages).**

Kunz, A., (2017). Misclassification and kappa-statistic: Theoretical relationship and consequences in application. Ludwig-Maximilians-Universitat Munchen Institut fur statistik **(31 pages).**

Lambin, E.F.; Geist, H.J.; Lepers, E., (2003). Dynamics of land-use land-cover change in tropical regions. Annu. Rev. Environ. Resour., 28: 205-244 **(40 pages).**

Li, X., (2010). Kappa-a critical review. Department of statistics, Uppsala University. **(30 pages).**

Long, H., Zhang, Y., Ma, L., & Tu, S. (2021). Land Use Transitions: Progress, Challenges and Prospects. *Land*, *10*(9), 903. **(20 pages)**

OECD, (2020). Towards sustainable land use: Aligning biodiversity, climate and food policies. OECD Publishing, Paris **(158 pages).**

Parniati, Managanta, A.A.; Tambingsila, M., (2022). The income and factors affecting the productivity of durian farmers. J. Agribisnis dan Ilmu Sosial Ekonomi Pertanian 7(5): 173-181 **(9 pages).**

Pingel, T., (2018). The raster data model. The geographic information science and technology body of knowledge. 3rd Quarter, John P. Wilson (Ed.) **(8 pages).**

Puno, G.R.; Puno, R.C.C., (2019). Watershed conservation prioritization using geomorphometric and land use-land cover parameters. Global J. Environ. Sci. Manage., 5(3): 279–294 **(6 pages).**

Rahmawaty; Rauf, A.; Sitorus; A.; Harahap, F.S; Walida, H. (2020). Land characteristics and land evaluation for development of the area of other uses (APL) in Siempat Rube Sub-district Pakpak Bharat District. IOP Conference Series: Earth Environ. Sci., 454: 012144 **(9 pages).**

Rakuasa, H.; Sihasale, D.A.; Somae, G.; Latue, P.C., (2023). Prediction of land cover model for central ambon city in 2041 using the cellular automata markov chains method. J. Geosains Remote Sens., 4(1): 1-10 **(10 pages).**

Rutebuka, J.; Uwimanzi, A.M.; Nkundwakazi, O.; Kagabo, D.M.; Mbonigaba, J.J.M.; Vermeir P.; Verdoodt, A., (2021). Effectiveness of terracing techniques for controlling soil erosion by water in rwanda. J. Environ. Manage., 277: 111369 **(12 pages).**

Saputra, M. H.; and Lee, H. S,. (2019). Prediction of land use and land cover changes for north sumatra, indonesia, using an artificial-neural-network-based cellular automaton. *Sustainability*, *11*(11), 3024 **(16 pages)**

Sari, D.D.S.; Jumadi; Anton., (2024). Analysis of settlement distribution pattern based on topography in Balik Bukit Subdistrict, West Lampung Regency. E3S Web of Conferences. 500: 02020 **(7 pages).**

Schirpke, U.; Tasser, E.; Borsky, S.; Braun, M.; Eitzinger, J.; Gaube, V.; Getzner, M.; Glatzel, S.; Gschwantner, T.; Kirchner, M.; Leitinger, G.; Mehdi-Schulz, B.; Mitter, H.; Scheifinger, H.; Thaler, S.; Thom, D.; Thaler, T., (2023). Past and future impacts of land-use changes on ecosystem services in austria. J. Environ. Manage., 345: 118728 **(14 pages).**

Shi, Y.; Zheng, Y; Chen, D.; Yang, J.; Cao, Y.; Cui, A., (2024). Research on the correlation between the dynamic distribution patterns of urban population density and land use morphology based on human-land big data: A case syudy of the Shanghai Central urban area. Land, 13, 1547. **(18 pages)**

Siagian, D.R.; Shrestha, R.P.; Shrestha, S.; Kuwornu, J.K.M., (2019). Factors driving rice land change 1989-2018 in the Deli Serdang Regency, Indonesia. Agriculture 2019, 9, 186 **(22 pages)**.

Tang, Z.; Wang, Y.; Fu, M.; Xue, J., (2023). The role of land use landscape patterns in the carbon emission reduction: Empirical evidence from China, Ecological Indicators, Vol. 156, 111176 **(12 pages)**.

Tsegaye, B., (2019). Effect of land use and land cover changes on soil erosion in Ethiopia. Int. J. Agric. Sci. Food Technol., 5(1): 026-034 **(9 pages).**

Verawaty, I.; Widiatmaka; Firmansyah I., (2023). Modeling of land use and cover changes (LUCC) in Deli Serdang Regency, North Sumatra Province. J. Nat. Resour. Environ. Manage., 13(2): 237-251 **(15 pages).**

Wu, H.; Lin, A.; Xing, X.; Song, D.; Li, Y., (2021). Identifying core driving factors of urban land use change from global land cover products and poi data using the random forest method. Int. J. Appl. Earthc Obs. Geoinf., 103: 102475 **(13 pages).**

Xiao, Y.; Huang, M.; Xie, G.; Zhen, L., (2022). Evaluating the impacts of land use change on ecosystem service values under multiple scenarios in the Hunshandake region of China. Sci. Total Environ., 850: 158067 **(14 pages).**

Zhang, Z.; Wei, Y.; Li, X.; Wan, D.; Shi, Z., (2024). Study on tianjin land-cover dynamic changes, driving factor analysis, and forecasting. Land. 13: 726 **(20 pages).**

Zhao, Y.; An, R.; Xiong, N.; Ou, D.; Jiang, C., (2021). Spatio-temporal land-use/land-cover change dynamics in coastal plains in Hangzhou bay area, China from 2009 to 2020 using google earth engine. Land. 10: 1149 **(31 pages).**

Zhou, H., Deng, Z., Xia, Y., and Fu, M. (2016). A new sampling method in particle filter based on Pearson correlation coefficient. Neurocomputing. 216: 208-215 (**8 pages**).

AUTHOR (S) BIOSKETCHES

Girsang, S.S.B., Ph.D., Research Professor, Research Center for Food Crops, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor 16915, Indonesia.
- Email: *seti011@brin.go.id*
- ORCID:0000-0003-2318-1273
- Web of Science ResearcherID: NA
- Scopus Author ID: 55795600300
- Homepage: brin.go.id

Banurea, D.M., M.Sc., Regional Research and Development Planning Agency, Pakpak Bharat Regency, Salak, 22272, Indonesia.
- Email: *berru.banurea@gmail.com*
- ORCID: 0009-0000-9383-7464
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: bappelitbangda.pakpakbharatkab.go.id

AUTHOR (S) BIOSKETCHES

Lestari, P., Ph.D., Research Professor, Research Center for Horticulture, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor 16915, Indonesia.
- Email: *puji016@brin.go.id*
- ORCID: 0000-0003-0615-4716
- Web of Science ResearcherID: NA
- Scopus Author ID: 6507413576
- Homepage: brin.go.id

Nambela, J.B., M.Sc., Assistant Research, Research Center for Estate Crops, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor 16915, Indonesia.
- Email: *juni006@brin.go.id*
- ORCID: 0000-0001-9568-1571
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: brin.go.id

Verawaty. I., M.Sc.., *Department of Agriculture, Deliserdang Regency, Lubuk Pakam, 20518, Indonesia*
- Email: *ivongnaga@gmail.com*
- ORCID: 0009-0002-5743-462x
- Web of Science ResearcherID: NA
- Scopus Author ID: 58644473700
- Homepage: deliserdangkab.go.id

Barus, J., Ph.D., Research Professor, Research Center for Food Crops, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor 16915, Indonesia.
- Email: *juni007@brin.go.id*
- ORCID: 0000-0003-3215-4541
- Web of Science ResearcherID: NA
- Scopus Author ID: 57207845427
- Homepage: brin.go.id

Jonharnas, B.Sc., Senior Research, Research Center for Food Crops, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor 16915, Indonesia
- Email: *jonh001@brin.go.id*
- ORCID: 0000-0001-9333-2140
- Web of Science ResearcherID: NA
- Scopus Author ID: 58524407200
- Homepage: brin.go.id

Girsang, M.A., M.Sc., Junior Researcher, Research Center for Cooperative, Corporation, and People's Economy, Research Organization for Governance, Economy, and Community Welfare, Indonesian National Research and Innovation Agency, Jakarta 12710, Indonesia
- Email: *mora001@brin.go.id*
- ORCID: 0000-0002-0628-7175
- Web of Science ResearcherID: NA
- Scopus Author ID: 57217525597
- Homepage: brin.go.id

Purba, T., M.S., Junior Researcher, Research Center for Cooperative, Corporation, and People's Economy, Research Organization for Governance, Economy, and Community Welfare, Indonesian National Research and Innovation Agency, Jakarta 12710, Indonesia
- Email: *tomm002@brin.go.id*
- ORCID: 0000-0002-2995-5498
- Web of Science ResearcherID: NA
- Scopus Author ID: 57216508617
- Homepage: brin.go.id

HOW TO CITE THIS ARTICLE

Girsang, S.S.; Nambela, J.; Lestari, P.; Banurea, D.M.; Verawaty, I.; Barus, J.; Jonharnas; Girsang, M.A.; Purba, T., (2025). Dynamics prediction of land use changes using cellular automata and artificial neural network modeling. Global J. Environ. Sci. Manage., 11(2): 427-442.

DOI: 10.22034/gjesm.2025.02.04

URL: https://www.gjesm.net/article_718949.html

Global J. Environ. Sci. Manage. 11(2): 443-460, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Eco-friendly biocontrol of Phytophthora capsici in black pepper (*Piper nigrum*) using Burkholderia species

Sukamto[1]; K.D. Sutanto[2,*], R. Noveriza[1], S. Hardiyanti[1], S.R. Djiwanti[1], Wiratno[2], D. Manohara[1], I.B. Rahardjo[2], R. Harni[1], W. Amaria[1], Supriadi[1]

[1] *Research Center for Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor, Cibinong, Indonesia*

[2] *Research Center for Horticulture, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor, Cibinong, Indonesia*

ARTICLE INFO

Article History:
Received 17 August 2024
Revised 21 November 2024
Accepted 24 December 2024

Keywords:
Eco-Friendly
Burkholderia sp.
Foot rot disease
Sustainable environment

DOI: 10.22034/gjesm.2025.02.05

ABSTRACT

BACKGROUND AND OBJECTIVES: *Phytophthora capsici* is a devastating pathogen that causes significant yield losses in black pepper (*Piper nigrum*) globally. In light of the increasing need for environmentally friendly substitutes for chemical fungicides, this research focused on evaluating the antagonistic properties of rhizobacteria isolated from the rhizospheres of black pepper in Bangka and Sukamulya, Indonesia. The objective is to establish sustainable management approaches to address *Phytophthora capsici*.

METHODS: A total of 520 rhizobacterial isolates were screened using dual culture assays to assess their antagonistic activity against *Phytophthora capsici*. The isolates demonstrating significant inhibitory effects, with over 70 percent reduction in radial growth, were subsequently analyzed to understand their mechanisms of action, which included the production of enzymes and the emission of volatile organic compounds. Cryo-field emission scanning electron microscopy was used to study the morphological effects on *Phytophthora capsici* mycelia. Biosafety assays were conducted to evaluate hemolytic activity and hypersensitive response induction. Molecular identification of the most potent isolate was performed using 16 small subunit ribosome deoxyribonucleic acid sequencing. Trials in a greenhouse setting were performed to determine the biocontrol effectiveness of the identified isolate in mitigating foot rot disease in black pepper plants.

FINDINGS: Out of 520 isolates, 37 showed antagonistic activity, with ten isolates inhibiting over 70 percent of *Phytophthora capsici* radial growth. Isolate *Burkholderia species* demonstrated the highest inhibition as 87.59 percent, mediated through enzyme production and volatile organic compound emission. Cryo-field emission revealed significant morphological abnormalities in *Phytophthora capsici* mycelia, such as lysis and shriveling. The eight effective isolates demonstrated non-hemolytic properties and did not provoke hypersensitive responses in tobacco leaves, confirming their suitability for biocontrol purposes. Physiological characterization revealed the production of chitinase, glucanase, and protease enzymes by these isolates. Molecular identification classified *Burkholderia species* a known biocontrol agent. Greenhouse trials revealed that *Burkholderia species* substantially lowered the incidence of foot rot disease, highlighting its potential in controlling *Phytophthora capsici*.

CONCLUSION: The findings conclusion demonstrate that *Burkholderia species* can serve as an effective and eco-friendly biocontrol agent, significantly reducing *Phytophthora capsici* infections. This study encourages the adoption of sustainable agricultural techniques and highlights the role of biological control in integrated disease management systems, with the goal of minimizing environmental harm and reducing reliance on chemical inputs.

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
46

NUMBER OF FIGURES
5

NUMBER OF TABLES
6

*Corresponding Author:
Email: *koko006@brin.go.id*
Phone: +6285700185612
ORCID: 0000-0002-3605-4954

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Foot rot disease, caused by *Phytophthora capsici*, is one of the most significant threats to black pepper (*Piper nigrum*) cultivation in Indonesia. This pathogen is capable of infecting all sections and stages of plant growth, from nursery plants to mature crops in agricultural settings (Suriany *et al.,* 2021). *Phytophthora capsici* is particularly challenging to control due to its ability to survive for years as oospores or chlamydospores in the soil. Furthermore, it swiftly produces zoospores in a timeframe of 3 to 5 days, allowing for several infection cycles and encouraging active movement toward plant roots (Lomaour *et al.,* 2012). Various approaches are employed to manage *P. capsici*, including the development of resistant varieties, cultural practices, fungicides, and biological control agents. Indonesia has yet to develop resistant varieties; however, some cultivars, like Perambramundi, are available. Indian institute of species research (IISR) Shakti, has shown resistance to *P. capsici* in other regions. Resistance mechanisms in these cultivars involve increased phenol, lignin, β-1,3-glucanase, and β-1,4-glucanase activity (Vandana *et al.,* 2014), as well as specific resistance genes like *piper nigrum* conserved nucleotide binding site (PnCBNS 4; PnCBNS 1) (Umadevi and Anandaraj, 2017), which hold promise as genetic markers for resistance breeding. Fungicides such as copper-based compounds, phenylamides (metalaxyl), and phosphonates (Fosetyl-aluminium, potassium phosphonate) are effective in controlling *P. capsici* in black pepper. However, prolonged fungicide use can lead to fungicide-resistant *P. capsici* mutants, as reported in potato plants treated with pyrimorph fungicides (Pang *et al.,* 2013). Biocontrol agents including *Burkholderia spp*., adhere to the principles of environmental management by decreasing chemical usage and enhancing ecological stability in agricultural practices (Singh *et al.,* 2017). This study emphasizes the environmentally beneficial properties of rhizobacteria and its role in promoting sustainable agricultural practices (Harish *et al.,* 2019). The adoption of *Burkholderia sp*. KB7 aligns with sustainable agriculture practices by promoting ecological balance (Huang *et al.,* 2021). This study contributes to the field of biocontrol by examining the synergistic interactions between volatile organic compounds (VOCs) and antifungal enzymes produced by *Burkholderia sp*., shedding light on the molecular mechanisms that facilitate enhanced suppression of pathogens (Sidorova *et al.,* 2022). Rhizobacteria reduce chemical dependency, aligning with sustainable agriculture principles and promoting resilient ecosystems (Tariq *et al.,* 2020). Rhizobacteria offer an eco-friendly alternative, reducing fungicide-related soil and water contamination (Huang *et al.,* 2021). In addition, the environmental and health risks associated with fungicides call for the adoption of environmentally sustainable control measures, including the application of biological control agents. Several rhizobacteria have demonstrated efficacy in suppressing *P. capsici*. For example, *Enterobacter cancerogenus*, *E. cloacae*, and *E. asburiae* were found to exhibit strong antagonistic effects against *P. capsici* in vitro (Toh *et al.,* 2016). *Bacillus megaterium* BP17, an endophytic bacterium isolated from black pepper roots in India, showed antagonism not only against *P. capsici* but also against other pathogens, including *Pythium myriotylum*, *Athelia rolfsii*, and *Ralstonia solanacearum* (Munjal *et al.,* 2016). Other bacteria, such as *Pseudomonas aeruginosa*, *P. putida* (Aravind *et al.,* 2008), and *Streptomyces spp*. (Zohara *et al.,* 2016). Chen *et al.* (2016), have also been effective against *P. capsici* in various crops. These bacteria adopt several mechanisms, including the synthesis of antibiotics, enzymatic lysis, competitive behavior, and the activation of systemic resistance (Dimkic *et al.,* 2022). This study focused on isolating rhizobacteria from the roots of black pepper, examining their antagonistic effects on *P. capsici* in both in vitro and in vivo settings, and identifying potential strains through the application of 16S rRNA gene sequencing. Developing an effective rhizobacterial strain with multiple suppression mechanisms offers a sustainable and eco-friendly solution for managing foot rot disease in black pepper. The study was conducted in Bogor City, West Java, Indonesia in 2022.

MATERIALS AND METHODS

Source of Phytophthora capsici isolate

The *P. capsici* isolate used in this study was obtained from black pepper infected leaves at the Balittro Seed Management Unit at Bogor, West Java Province (S 6° 35’ 20.9976”, E 106° 47’ 34.7964”). For the initial isolation of fungi, symptomatic leaves were incubated on water agar media, and subsequently, they were transferred to potato dextrose agar (PDA) for subculturing. Koch’s postulates were confirmed

through pathogenicity tests on pepper leaves. The isolate's identity was verified using ITS6 (forward) (GAAGGTGAAGTCGTAACAAGG) and ITS4 (reverse) primer (TCCTCCGCTTATTGATATGC) (Sheji *et al.,* 2000), as per standard molecular identification protocols.

Isolation of Rhizobacteria

Rhizobacteria were isolated from pepper roots collected in Bangka, Bangka-Belitung Islands Province and Sukamulya, West Java Province. Root and adhering soil samples as 10 grams (g) were homogenized in sterile water, serially diluted, and plated on selective media, including *Pseudomonas* Agar P (DifcoTM 244910), Actinomycetes Isolation Agar (DifcoTM 212168), King B Medium (*Pseudomonas F* agar), and *Bacillus* medium (Szczech and Shoda, 2005). *Burkholderia sp. KB7* was selected for its established effectiveness in generating antifungal metabolites and its capacity to thrive in a range of environmental conditions (Huang *et al.,* 2020; Chauhan *et al.,* 2023). The roots, along with the attached soil, were cut into small segments weighing ten grams in total and then put in an Erlenmeyer flask containing 90 ml of sterile water. After an hour of shaking, a serial dilution was executed by taking one milliliter and adding it to nine milliliters of sterile water. At the 3rd and 4th dilutions, 50 microliters (µl) of the solution was taken and spread using a triangular glass on the media of each medium in Petri dishes as 9 centimeters (cm) in diameter). Subsequent to incubation at room temperature, the bacterial colonies were kept at 4 degrees Celsius (°C) for additional examination.

Screening of Rhizobacteria against P. capsici

The antagonistic activity of rhizobacterial isolates was tested against *Phytophthora capsici* and using the dual culture method following the procedure described by Thampi and Bhai (2017). *Rhizobacteria* and *P. capsici* were inoculated on a PDA medium in Petri dishes, positioned 3 cm apart

Incubation of the plates occurred at 30°C, while *P. capsici* was cultivated separately in distinct Petri dishes acting as the control group. The measurement of the pathogen's radial growth was conducted at the point when the mycelial growth in the control reached the dish's edge. The experiment was conducted in triplicate. The percentage inhibition of *P. capsici* growth was calculated using Eq. 1 (Admassie *et al.,* 203):

$$I = (C-T)/C \times 100 \quad (1)$$

I = Percent (%) inhibition, C= radial growth (mm) of the *P. capsici* in control, and T = radial growth of the *P. capsici* in treatment.

The evaluation of VOC production from rhizobacterial isolates was performed in accordance with the procedures outlined by Safitri *et al.* (2023). Rhizobacteria were cultured on starch casein agar (SPA) medium in one plate, while three mycelial plugs of *P. capsici* as 5 millimeters (mm) in diameter) were inoculated on PDA medium in another plate. The SPA plates containing Rhizobacteria were turned upside down onto the PDA plates that had *P. capsici*, and the two plates were tightly sealed together using Parafilm strips. The sealed plates were incubated at room temperature for six days. The radial growth inhibition of *P. capsici* was measured when the growth in the control reached the edge of the Petri dish. The experiment was conducted three additional times to confirm its reproducibility. To investigate the effects of antagonistic rhizobacteria on *P. capsici* mycelium, observations were conducted using a cryo-field emission scanning electron microscope (Cryo-FESEM). Mycelium samples of *P. capsici* were collected from the inhibition zone, which is within 2 mm of the inhibited growth front, on plates exposed to antagonistic rhizobacteria. Control samples were taken from untreated cultures of *P. capsici*. Mycelial samples were fixed in liquid nitrogen for 90 seconds and then transferred to the vacuum chamber of a Cryo-FESEM (JSM-530LV, JEOL Ltd., Tokyo, Japan) for detailed morphological observations.

Biological safety test

In order to confirm the biological safety of the Rhizobacterial isolates, two assessments were carried out: hemolysis and hypersensitivity reaction (HR). Each isolate was streaked onto blood agar medium to conduct the hemolysis test, with observations made for the presence of clear or cloudy zones around the colonies (Amaria *et al.,* 2023). The existence of these zones signifies a favorable response, indicating that the bacteria possess the capability to break down components of red blood cells. The HR test involved injecting 1 milliliter (mL) of a 24-hour-old

Rhizobacterial suspension (prepared in sucrose peptone broth) into the underside of tobacco leaves. After incubating the leaves for 24 to 48 hours, the development of necrotic patches was documented as a sign of a positive hypersensitivity reaction. Only isolates that tested negative for both hemolysis and HR were selected for further experiments.

Characterization of Rhizobacteria

The enzymatic activities and phosphate solubilization abilities of the rhizobacterial isolates were assessed using standard protocols.

Chitinase production

Colloidal chitin was prepared from commercial chitin (034-13632, Wako) following the method described by Joe and Sarojini (2017). Agar medium containing 0.5% colloidal chitin, 0.1% monopotassium phosphate (KH_2PO_4), 0.01% magnesium sulfate ($MgSO_4 \bullet 7H_2O$), 0.05 g yeast extract, 0.1 g peptone, 0.1 g bacto-tryptone, 0.025% NaCl, 0.1 g $(NH_4)_2SO_4$, and 1.5% agar was used for the qualitative detection of chitinase activity. Spot inoculation was performed with each rhizobacterial isolate on the medium, followed by incubation at room temperature for four days. The resulting clear zones of chitin hydrolysis surrounding the bacterial colonies were a sign of chitinase activity.

Protease production

Protease activity was determined using skim milk agar (SMA) medium, prepared with 15 g skim milk, 0.5 g yeast extract, 15 g agar, and 1 L distilled water, as described by Ghodsalavi *et al.* (2013). SMA plates were inoculated with rhizobacterial isolates and kept at room temperature for three days. The formation of clear zones around the bacterial colonies indicated the occurrence of protease activity.

Phosphate solubilization

Phosphate solubilization ability was tested by inoculating the rhizobacterial isolates on Pikovskaya agar medium (Fatimah *et al.*, 2023). Upon completion of three days of incubation, clear zones were detected around the bacterial colonies, demonstrating the occurrence of phosphate solubilization.

Greenhouse assay

The efficacy of eight highly antagonistic rhizobacterial isolates against *P. capsici* was evaluated in a greenhouse using the Petaling 1 black pepper variety, which is susceptible to foot rot disease. The planting medium consisted of sand, soil, and manure in a 2:1:1 ratio, inoculated with *P. capsici* zoospores (10^6 spores g^{-1}). The experiment was designed as a completely randomized trial with 10 rhizobacterial treatments, each replicated three times. Black pepper cuttings were soaked in bacterial suspensions as 10^8 colony forming unit per milliliter (CFU/mL) for 30 minutes (min.) and then subsequently planted in inoculated planting media. In each treatment, 20 plants were placed in each pot, and the incidence of disease was observed for a month after inoculation. The focus of the observations was on the emergence and advancement of foot rot disease.

16S rDNA Gene sequence analysis

Molecular identification of the rhizobacterial isolates was conducted using 16 small unit deoxyrobonuclease acid (16S rDNA) sequencing. Following the methodology established by Packeiser and Lim (2013), bacterial deoxyribonucleic acid (DNA) was extracted utilizing the colony polymerase chain reaction (PCR) approach. The 16S rDNA gene of isolate KB-4 was amplified using the primers 27F (5'-AGAGTTTGATCCTGGCTCAG-3') and 1492R (5'-GGTTACCTTGTTACGACTT-3') in a PCR using GoTaq DNA polymerase (Promega), as outlined by Palaniappan *et al.* (2010). The PCR program consisted of 30 cycles of denaturation at 95°C for 10 seconds, annealing at 56°C for 30 seconds, and extension at 72°C for 45 seconds, followed by a final extension step at 72°C for five minutes. The amplified fragments were sequenced using an ABI PRISM 3130 Genetic Analyzer (Applied Biosystems). The analysis of DNA sequences was conducted using the basic local alignment search tool (BLAST) provided by the National Center for Biotechnology Information (NCBI) to identify various bacterial species. Phylogenetic relationships were determined using the neighbor-joining method in MEGA version 7 software.

Statistical analysis

The statistical analysis was conducted to evaluate the effects of rhizobacterial isolates on disease suppression and inhibition of *Phytophthora capsici* in pepper plants. All experimental data, including healthy plants, infected plants, disease incidence (%),

disease suppression (%), and inhibition percentage (%), were subjected to analysis of variance (ANOVA) using statistical package for the social sciences (SPSS) software (version 20). Following ANOVA, Duncan's multiple range test (DMRT) was applied at a 5% significance level ($p < 0.05$) to determine significant differences between the treatments. An analysis of mean separation was carried out to assess how different isolates influence disease incidence and suppression parameters.

RESULTS AND DISCUSSION

Isolation and antagonistic activity of rhizobacteria

Five hundred and twenty (520) rhizobacterial isolates were obtained from the rhizosphere of black pepper plants collected from Bangka Belitung and Sukabumi, West Java. These isolates were screened in vitro to evaluate their antagonistic potential against *Phytophthora capsici*. A dual culture assay was employed to assess the antagonistic activity of the rhizobacterial isolates. From a total of 520 isolates, 37 showed significant inhibition of *P. capsici* growth, as presented in Table 1.

Antagonistic activity of selected Rhizobacterial isolates

Ten rhizobacterial isolates, namely B-KB2, B-KB3, B-KB4, S-KB6, S-KB7, S-KB9, B-ACT2, S-KB10, S-ACT7, and S-SPA2, exhibited strong antagonistic activity against *P. capsici*, with inhibition percentages

Table 1: Percentage reduction of *P. capsici* radial growth by antagonistic rhizobacterial isolates

No	Isolate	Source plant	Diameter of *P. capsici* (mm)	Inhibition zone o (mm)	Inhibition of diameter growth
1	B-KB1	Kamboja-2, Bangka	31.35a	2.22i	34.52k
2	B-KB2	Kamboja-3, Bangka	13.37n	16.63e	72.34e
3	B-KB3	KP-1, Bangka	12.67n	17.33d	73.79d
4	B-KB4	KP-1, Bangka	5.99n	24.01a	87.59a
5	B-KB5	KP-2, Bangka	28.39d	1.61i	41.25i
6	B-ACT1	Kamboja-2, Bangka	25.80fg	5.11g	46.62h
7	B-ACT2	Kamboja-2, Bangka	11.850	18.15d	75.48d
8	B-ACT3	Kamboja-3	24.81hij	5.19g	48.67f
9	B-ACT4	KP-1	26.50f	4.22h	45.17h
10	S-KB1	Sukamulya-1	28.38c	1.81i	41.30hi
11	S-KB2	Sukamulya-1	23.04k	6.96f	52.33e
12	S-KB3	Sukamulya-1	24.81i	5.20g	48.67f
13	S-KB4	Sukamulya-1	26.93e	3.07i	44.27h
14	S-KB5	Sukamulya-1	31.79a	2.12i	34.21k
15	S-KB6	Sukamulya-1	6.00p	23.05b	87.58a
16	S-KB7	Sukamulya-2	7.33p	22.67b	84.83b
17	S-KB8	Sukamulya-2	24.98h	5.02g	48.31g
18	S-KB9	Sukamulya-2	7.33p	22.67b	84.83b
19	S-KB10	Sukamulya-2	8.33p	21.00c	82.76c
20	S-KB11	Sukamulya1	27.9d	2.10i	42.27h
21	S-KB12	Sukamulya1	28.39c	1.61i	41.25i
22	S-KB13	Sukamulya1	25.27gh	4.73h	47.29
23	S-KB14	Sukamulya-2	29.86b	1.22k	38.22j
24	S-ACT1	Sukamulya-1	20.86l	9.14f	56.83e
25	S-ACT2	Sukamulya-1	24.6ij	5.40g	49.09f
26	S-ACT3	Sukamulya-1	24.6j	5.40g	49.09f
27	S-ACT4	Sukamulya-1	27.86d	2.14i	42.36h
28	S-ACT5	Sukamulya-1	25.35gh	4.65h	47.54g
29	S-ACT6	Sukamulya-3	18.36m	11.64f	62.01e
30	S-ACT7	Sukamulya-3	10.210	19.79d	78.86c
31	S-ACT8	Sukamulya-3	20.70l	9.00f	57.17e
32	S-ACT9	Sukamulya-3	29.85b	1.80i	38.23j
33	S-ACT10	Sukamulya-3	24.11ij	5.89g	50.11e
34	S-SPA1	Sukamulya-1	27.6d	2.40i	42.89h
35	S-SPA2	Sukamulya-1	10.110	19.89c	79.08c
36	S-SPA3	Sukamulya-2	25.83fg	4.17h	46.55
37	S-SPA4	Sukamulya-2	24.35j	5.65g	49.62f

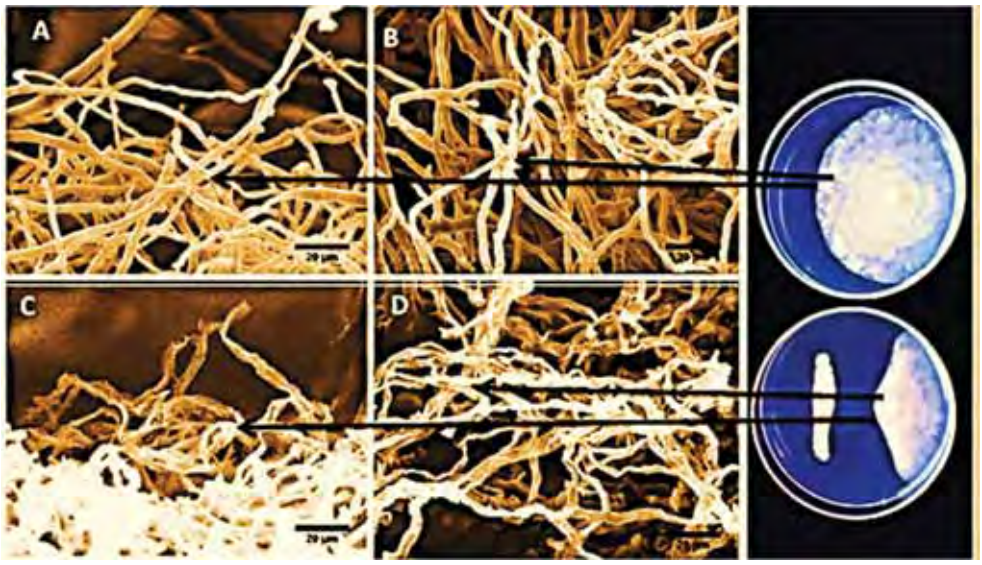


Fig. 1: Microscopic observations of the interaction between antagonistic Rhizobacteria isolate KB7 and *Phytophthora capsici*: A and B show normal hyphae, C and D show hyphal swelling and lysis

exceeding 70%. Among these, isolates B-KB4, S-KB6, S-KB7, S-KB9, and S-KB10 demonstrated particularly high levels of antagonism, with inhibition rates ranging from 82.76% to 87.59%. Microscopic analysis revealed abnormal morphological features in *P. capsici* mycelia grown in dual culture with rhizobacteria (KB7), compared to those grown in isolation. The mycelial structures of *P. capsici* adjacent to the rhizobacterial culture exhibited notable structural irregularities, characterized by the presence of empty and shriveled hyphae (Fig. 1C). Additionally, lysis was detected roughly 3 mm from the growth tip Fig. 1D. In contrast, normal mycelial growth was observed in the control without rhizobacterial interaction (Fig. 1A, 1B). These findings suggest that the rhizobacterial isolates synthesize and release antibiotics, lytic enzymes, or other secondary metabolites capable of suppressing *P. capsici* growth. Previous studies have demonstrated the ability of rhizobacteria to suppress *P. capsici* effectively. For example, Toh *et al.* (2016) demonstrated that endophytic *Enterobacter sp*. reduced *P. capsici* growth by 43.33%–47.63%. Similarly, *Streptomyces sp*. was reported to inhibit the growth of *P. capsici* and *Sclerotium rolfsii* in black pepper, achieving inhibition rates exceeding 90% (91%–94%) (Thampi and Bhai, 2017). *Burkholderia sp*. KB7 significantly reduced the sporulation and growth of *Phytophthora capsici* under controlled conditions, demonstrating its promise as an effective biocontrol agent (Khatun *et al.,* 2018). Furthermore, biocontrol agents such as *Burkholderia spp*. enhances sustainable farming practices by decreasing reliance on chemical inputs and encouraging ecological stability (Tariq *et al.,* 2020).

In testing using the double plate assay method to detect volatile compounds, it was found that nine rhizobacterial isolates (KB-2, KB-3, KB-4, KB-6, KB-7, KB-10, ACT2, ACT7, and SPA2) produced low levels of volatile compounds, with inhibition ranging from 0.84% to 14.02%. Conversely, isolate KB-7 showed the most pronounced inhibitory effect on the growth of *P. capsici* through bacterial volatile compounds, with an inhibition rate of 56.52% (Fig. 2). These findings demonstrate that isolate KB-7 can produce and emit volatile organic compounds, which are instrumental in hindering the proliferation of *P. capsici*. Volatile compounds produced by bacteria can travel through the air, soil, or plant tissue (Giorgio *et al.,* 2015). In in vivo experiments, the bacterial volatile compounds from Bacillus amyloliquefaciens reduced the incidence of anthracnose disease (*Colletotrichum lindemuthianum*) by up to 85% (Martin *et al.,* 2019). Isolated from *Bacillus amyloliquefaciens*, the volatile compounds, including 3-methylbutanoic acid and 2-methylbutanoic acid, are toxic to these pathogens when administered alone or in combination.

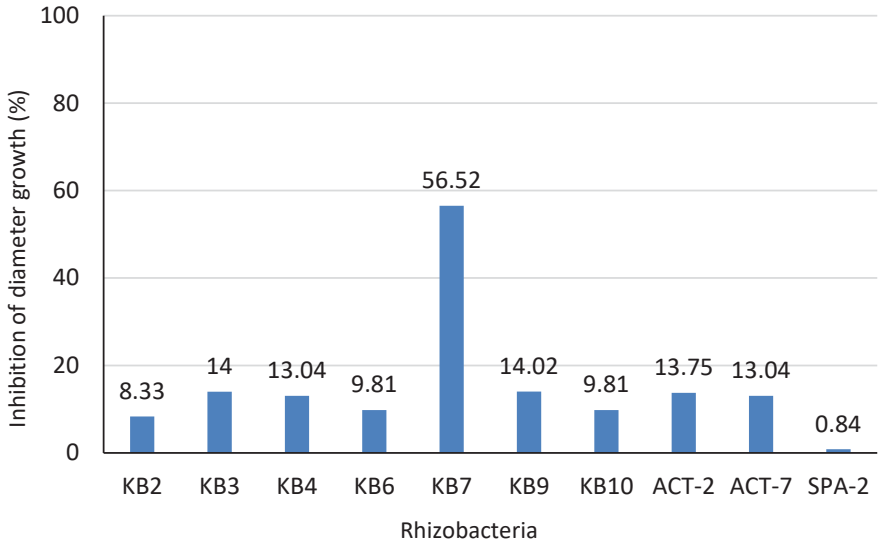


Fig. 2: The inhibition of mycelial growth diameter of *P. capsici* after 6 days of exposure to rhizobacterial volatiles on PDA medium

Consequently, volatile compounds produced by bacteria may serve as biological agents for the management of plant diseases. The biochemical pathways of key antifungal enzymes such as chitinases and glucanases will be elaborated, alongside the detailed composition of VOCs identified, such as 2,3-butanediol and phenolic derivatives, to provide a comprehensive mechanistic understanding (Sidorova *et al.,* 2022). Evidence from studies shows that *Burkholderia spp*. pose no toxicity risks to crops or humans, reinforcing their suitability for use in food production systems (Glick *et al.,* 2020).

Biosafety of rhizobacteria

Ten rhizobacterial isolates that showed strong antagonistic properties against *Phytohthora capsici* were tested for their biosafety. Among those rhizobacteria isolates, two isolates (KB3 and ACT2) produce β-hemolysis toxinIn the hypersensitive response testing, none of the isolates exhibited symptoms of necrosis. Consequently, eight isolates that demonstrated both negative hemolysis and negative hypersensitivity test results were selected for further investigation.

Physiological analysis of antagonistic rhizobacteria against P. capsici

Isolates exhibiting strong antagonistic activity against *P. capsici* were tested for their physiological properties. Nine isolates of rhizobacteria were found to produce chitinase, as shown by the presence of clear zones around the bacterial colonies, with halo diameters varying from 1.223 to 4.7875 mm (Table 2). Glucanase production was observed in nine rhizobacterial isolates, with halo diameters ranging from 2.00 to 3.58 mm. Protease enzymes were produced by eight rhizobacterial isolates, namely B-KB4, S-KB6, S-KB7, S-KB10, ACT2, ACT7, and S-SP2. Chitinase, glucanase, and protease are enzymes capable of degrading the cell walls of pathogenic fungi and are secreted by rhizobacteria, making them useful in biocontrol.

Fig. 3 shows that rhizobacterial isolates effectively reduced the disease intensity of *Phytophthora capsici* in black pepper. Isolate KB-4 (KP-1, Bangka) achieved 100% suppression, followed by KB-9 (Sukamulya-2) with 94.74%. Isolates KB-6, KB-7, and KB-10 each reduced disease intensity to 10% (89.47% suppression). ACT-2 (Kamboja-2) and SPA-2 also showed moderate suppression, while ACT-7 was the least effective. The absence of disease in the negative control confirmed the biocontrol efficacy of the isolates. Effect of rhizobacterial treatments on disease intensity (%) caused by Phytophthora capsici. KB3 and KB4 completely suppressed disease (0%), while isolates KB7, KB9, KB6, and KB10 significantly

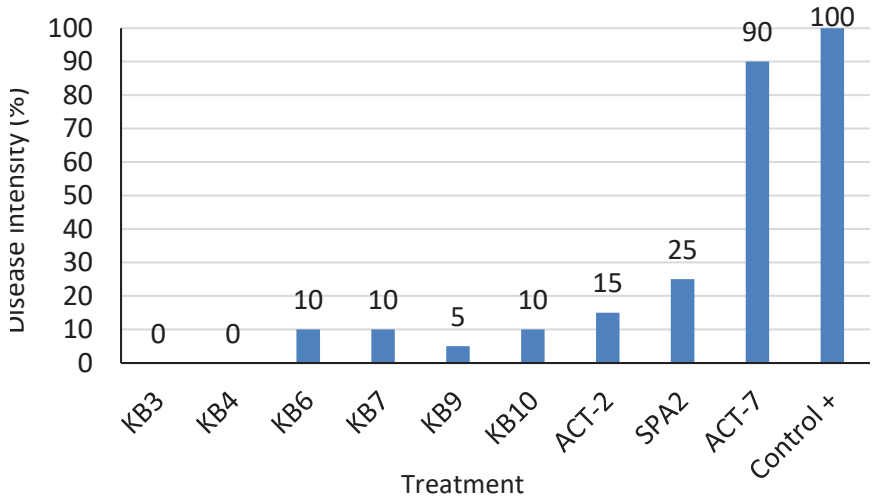


Fig. 3: Disease intensity (%) of *P. capsici* after treatment with different rhizobacterial isolates

Table 2: Biochemical and antagonistic properties of rhizobacterial isolates for biocontrol applications

No	Isolate	Glucanase	Chitinase index	Glucanase index	Protease	Phosphate solubilization	HR	Hemolysis
1	B-KB-2	0f	3.1250bc	0j	0.00d	0.00f	-	-
2	B-KB-3	2.20d	4.7875a	3.8300b	0.00d	0.00f	-	+
3	B-KB-4	2.30d	3.0250c	2.4200g	2.29c	6.00b	-	-
4	S-KB-6	3.58a	3.0500c	3.9778a	2.33b	6.00b	-	-
5	S-KB-7	2.00e	1.2330d	1.1100i	2.57a	7.33a	-	-
6	S-KB-9	3.58a	4.2500a	3.5800c	0.00d	4.33c	-	-
7	S-KB-10	2.75bc	3.4375b	2.5000f	0.00d	1.34e	-	-
8	S-ACT-2	2.75bc	3.4375b	2.9375d	0.00d	0f	-	+
9	S-ACT-7	2.94b	3.6718b	2.7560e	0.00d	0f	-	+
10	S-SP2	2.52c	3.4000bc	2.1500h	0.00d	2.33d	-	-

reduced disease intensity (5%–15%). SPA-2 showed limited efficacy (25%), whereas ACT-7 and untreated control groups recorded the highest intensities (90% and 100%, respectively.

Rhizobacterial isolates exhibited diverse enzymatic activities and growth-promoting traits (Table 3). Isolate KB-3 had the highest glucanase index (3.83) and strong siderophore production (+++), while KB-4 and KB-6 showed high protease indices (4.33 and 4.66, respectively) and phosphate solubilization abilities (6.00). Isolates such as KB-7, KB-9, and KB-10 demonstrated combined enzymatic activities and plant growth-promoting traits, including siderophore production, IAA, and ACC deaminase activity, making them promising candidates.

All tested isolates exhibited antifungal activity against *Phytophthora capsici* (Table 4). KB-4 had the highest inhibition zone (24.01 mm) and inhibition percentage (87.59%). Other effective isolates included KB-7 (22.67 mm, 84.83%) and KB-9 (19.67 mm, 78.62%). Moderate inhibition was observed in isolates like B-KB2 (16.63 mm, 72.34%) and S-SPA2 (19.89 mm, 79.08%). These findings indicate significant biocontrol potential against *P. capsici*. An in-depth examination has been conducted on the biochemical pathways and molecular mechanisms that contribute to the biocontrol efficacy of *Burkholderia sp. KB7*. Key mechanisms include the action of hydrolytic enzymes such as chitinases and glucanases, which effectively degrade fungal cell walls, and the production of VOCs like 2,3-butanediol, which disrupt fungal growth and interfere with critical signaling pathways (Sidorova *et al.,* 2022). These findings correspond with those from related studies that emphasize the critical role

Table 3: Enzymatic activities and plant growth-promoting traits of rhizobacterial isolates

Isolates	Chitinase index	Protease index	Glucanase index	Phosphate Solubilization index	Siderophore Production	IAA Production	ACC Deaminase Production
KB-2	1.50	0.00	2.72	0.00	-	-	-
KB-3	3.00	0.00	3.83	0.00	+++	+	-
KB-4	2.00	4.33	2.42	6.00	++	-	+
KB-6	1.50	4.66	ND	6.00	-	-	-
KB-7	2.00	5.00	1.11	7.33	+++	_	+
KB-9	1.56	3.50	3.58	4.33	+++	+	+
KB-10	1.55	3.56	2.75	1.34	+++	+	+
ACT-2	2.02	4.33	2.75	1.42	+++	-	
ACT-7	1.56	3.60	2.97	1.44	-	-	
SP2	1.33	2.22	ND	2.33	-	-	

Table 4: Antifungal activity of rhizobacterial isolates against *Phytophthora capsici*: Inhibition zones and percentages

No.	Isolate	Source plant	*P. capsici* (mm)	Inhibition zone of rhizobacteria (mm)	Inhibition percentage
2	B-KB2	Kamboja-3, Bangka	13.37a	16.63e	72.34cd
3	B-KB3	KP-1, Bangka	12.67b	17.33e	73.79d
4	B-KB4	KP-1, Bangka	5.99f	24.01a	87.59a
7	B-ACT2	Kamboja-2, Bangka	11.85c	18.15d	75.48bc
15	S-KB6	Sukamulya-1	13.71a	16.29e	71.63d
16	S-KB7	Sukamulya-2	7.33e	22.67b	84.83a
18	S-KB9	Sukamulya-2	10.33d	19.67c	78.62b
19	S-KB10	Sukamulya-2	11.33c	18.67cd	76.55bc
30	S-ACT7	Sukamulya-3	10.21d	19.79c	78.86b
35	S-SPA2	Sukamulya-1	10.11d	19.89c	79.08bc

of enzyme activity and VOC generation in strategies for microbial biocontrol (Chandrasekaran *et al.,* 2022). The application of these mechanisms in real-world settings faces obstacles like environmental variability and formulation stability. Addressing these issues requires the implementation of advanced bioprocessing techniques to guarantee reliable performance (Tariq *et al.,* 2020).

Molecular analysis of isolate KB-7

Isolate KB-7 has a 1,390 bp sequence based on 16S rDNA. A comparison of the 16S rDNA sequence with other bacteria in the GeneBank database using BLASTN analysis showed that the KB-7 rhizobacterial isolate has a 99% similarity with all species of *Burkholderia sp*. Utilizing MEGA 7 software for phylogenetic analysis, it has been determined that isolate KB-7 is closely associated with various species of *Burkholderia sp*. (Fig. 4). In contrast, comparisons with bacteria from other species, such as *Pseudomonas sp*., *Bacillus sp*., *Streptomyces sp*., *Serratia sp*., and *Stenotrophomonas sp*., revealed lower sequence similarities, ranging from 79% to 85% (Table 5). Prolonged testing has illustrated the steady performance of *Burkholderia sp*. KB7 across different cropping seasons, affirming its trustworthiness in biocontrol strategies (Solano *et al.,* 2009). A comparative analysis of Burkholderia spp. against other biocontrol agents such as *Pseudomonas fluorescens* and *Bacillus subtilis* will be included to provide a broader context of its efficacy and application potential (Khatun *et al.,* 2018). Utilizing Burkholderia species as a biocontrol agent over an extended period boosts soil microbial diversity and lessens the need for synthetic fungicides, which frequently lead to negative environmental consequences (Nazli *et al.,* 2020; Sabalpara and Mahatma, 2019). This suggests that isolate KB-7 is most likely identified as *Burkholderia sp*., a genus of bacteria in the Proteobacteria phylum, specifically the Betaproteobacteria class. This genus has a complex taxonomy with over 80 known species. Rhizobacteria are generally divided into two subclasses:

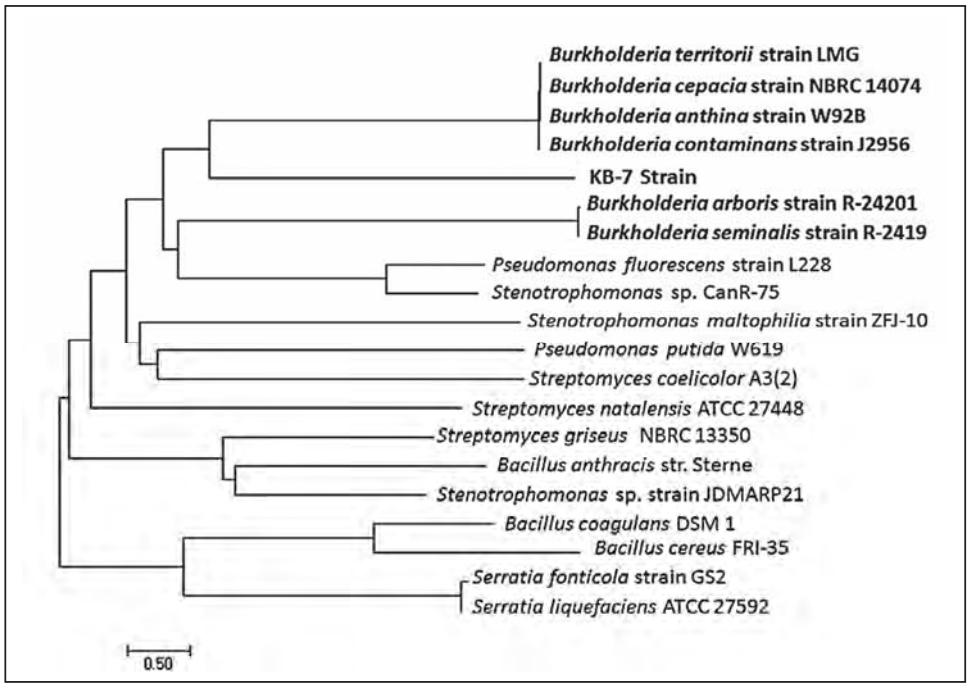


Fig. 4: Dendrogram of the phylogenetic relationship of rhizobacterial Isolate KB-7 with other bacteria based on 16S rDNA sequence

Table 5: Sequence similarity of 16S rDNA of Isolate KB-7 with several rhizobacterial species

No.	Bacteria	Accession number	Homology (%)
1	*Burkholderia contaminans* strain J2956	NR_104978.1	99
2	*Burkholderia contaminans* strain RA_07A1.3	KT719943.1	99
3	*Burkholderia territorii* strain LMG	NR_136496.1	99
4	*Burkholderia lata* strain 383	NR_102890.1	99
5	*Burkholderia cepacia* strain NBRC 14074	NR_113645.1	99
6	*Burkholderia metallica* strain R-16017	NR_042636.1	99
7	*Burkholderia arboris* strain R-24201	NR_042634.1	99
8	*Burkholderia seminalis* strain R-2419	NR_042635.1	99
9	*Burkholderia anthina* strain W92B	NR_104975.1	99
10	*Burkholderia ambifaria* strain AMMD	NR_074687.1	99
11	Burkholderia latens strain R-5630	NR_042632.1	99
12	*Burkholderia cenocepacia* strain BAAr-207	KY810676.1	99
14	*Pseudomonas putida* W619	NC_010501.1	84
15	*Pseudomonas fluorescens* strain L228	NZ_CP015639.1	85
16	*Bacillus coagulans* DSM 1	NZ_CP009709.1	81
17	*Bacillus anthracis* str.	NC_005945.1	81
18	*Bacillus cereus* FRI-35	NC_018491.1	81
19	*Streptomyces coelicolor* A3(2)	NC_003888.3	79
20	*Streptomyces natalensis* ATCC 27448	NZ_JRKI01000044.1	80
21	*Streptomyces griseus subsp. griseus* NBRC 13350	NC_010572.1	80
22	*Serratia fonticola* strain GS2	NZ_CP013913.1	83
23	*Serratia liquefaciens* ATCC 27592	NC_021741.1	83
24	*Stenotrophomonas sp*. strain JDMARP21	KX817899.1	85
25	*Stenotrophomonas sp.* CanR-73	KT580665.1	85
26	*Stenotrophomonas maltophilia* strain ZFJ-10	EU931549.1	85
27	*Stenotrophomonas sp.* CanR-75	KT580667.1	85

Notes: BI=Botanical insecticide; SI=Synthetic insecticide, DAA=day after application



Fig. 5: Testing of VOCs from bacterial isolates KB4 (left) and KB7 (center), and control (right) against *P. capsici* infection

Alphaproteobacteria, which include Agrobacterium, Allorhizobium, Azorhizobium, Bradyrhizobium, Mesorhizobium, Rhizobium, and Sinorhizobium (Willems, 2006), and Betaproteobacteria, which include Burkholderia, Cupriavidus, and Ralstonia (Chakraborty *et al.,* 2020). Wang *et al.* (2023) reported that *Burkholderia sp*., a rhizobacterial species, is the first from the Betaproteobacteria subclass capable of forming a symbiotic relationship by colonizing plant roots. Additional genomic investigations of *Burkholderia sp*. KB7 uncover pathways associated with its antifungal characteristics and adaptability to various soil environments (Singh, 2017). Efficacy studies demonstrates a strong link between soil conditions and bacterial activity, underscoring the necessity for specialized field applications (Nazli *et al.,* 2020).

Table 6 shows disease incidence (%) and disease suppression (%) on the Inhibition of *P. capsici* Infection in Pepper Plants. is one of the species included in Plant Growth Promoting Bacteria (PGPB), a group of bacteria that positively influence plant growth and development without causing negative effects on the host or the environment (Bernabeu *et al.,* 2015). The growth of plants is stimulated by these rhizobacteria via various strategies, such as fixing nitrogen from the atmosphere, producing phytohormones, and synthesizing antibiotics that can limit the growth of pathogenic microbes. Field trials demonstrate that optimal moisture and neutral pH levels significantly enhance the activity of Burkholderia species, while extreme conditions can reduce its effectiveness (Nazli *et al.,* 2020). Kumar *et al.* (2017) reported that *Burkholderia sp*. can suppress wilt diseases caused by *Fusarium sp*. and enhance yields in *Trigonella foenum-graecum* L. *Burkholderia sp*., along with Pseudomonas sp., has also been shown to increase banana resistance to wilt disease caused by *Fusarium oxysporum* f.sp. *cubense* (Fishal *et al.,* 2010). In addition, it has been documented that *Burkholderia sp*. serves as a biofertilizer, promoting growth and boosting yields in multiple crops, including corn, banana, and sorghum (Santos *et al.,* 2017; Fu *et al.,* 2017; Naveed *et al.,* 2015; Young *et al.,* 2013). Synergistic interactions between Burkholderia spp. and other rhizobacteria like Pseudomonas can improve pathogen suppression and enhance plant health (Singh *et al.,* 2017).

Results from the tests revealed that isolate KB7 consistently demonstrated its ability to inhibit the growth of *P. capsici* on pepper leaves (Fig. 5). Testing the efficacy of VOCs from bacterial isolates KB4 (left) and KB7 (center) compared to the untreated control (right) against *Phytophthora capsici* infection.

Table 6: Effect of Rhizobacterial Isolates on the Inhibition of *Phytophthora capsici* Infection in Pepper Plants

No.	Isolate code	Origin	Healthy plants	Infected plants	Disease incidence (%)	Disease suppression (%)	Inhibition percentage (%)	Notes
1	KB-2	Bnk	18c	2e	10e	78.95e	42.19c	***
2	KB-4	KP-1, Bnk	20a	0g	0f	100.00a	46.76b	***
3	KB-3	KP-1, Bnk	13d	7b	35d	63.16e	46.76b	***
4	KB-6	Sukamulya-1	18c	2e	10e	89.47b	45.45b	***
5	ACT-2	Kamboja 2, Bnk	17b	3d	15d	84.21b	48.70a	***
6	KB-7	Sukamulya-2	18c	2e	10e	89.47b	45.45b	***
7	KB-9	Sukamulya-2	19b	1f	5f	94.74a	49.35a	***
8	KB-10	Sukamulya-2	18c	2e	10e	89.47b	43.50c	***
9	ACT-7	Sukamulya-3	2e	18a	90b	5.26f	40.00d	***
10	SPA-2	Sukamulya-1	15d	5c	25c	73.68d	43.33c	***
11	Positive Ctrl	N/A	1e	19a	95a	0g	0	-
12	Negative Ctrl	N/A	20a	0g	0f	0g	0	-

The isolates demonstrated significant inhibition of fungal growth, with KB7 showing the highest suppression. *Burkholderia sp*. KB7 complies with regulatory standards for microbial biocontrol agents, ensuring its safety for agricultural use (Khatun *et al.,* 2018). Utilizing Burkholderia spp. alongside other control agents or organic amendments can lead to substantial improvements in disease management efforts (Singh *et al.,* 2021). Bioassays conducted in the laboratory indicate that there is minimal impact on beneficial insects and non-target plants, which supports ecological compatibility (Glick *et al.,* 2020). This indicates that isolate KB7 can suppress fungal growth and the rate of root rot disease in pepper by producing VOCs. The present findings highlighted the potential of rhizobacteria, especially *Burkholderia sp*. KB7, as a sustainable and eco-friendly biocontrol agent against *P. capsici*, therefore, offers promising applications in integrated disease management and sustainable pepper cultivation practices. The effectiveness of *Burkholderia spp*. in disease management frameworks can be enhanced through the integration of compost amendments and the practice of crop rotation (Singh *et al.,* 2021). Field trials optimized the application timing *of Burkholderia sp*. KB7 to align with peak pathogen activity, maximizing its biocontrol efficacy (Nazli *et al.,* 2020). Building on this, recent studies have highlighted the role of specific VOCs and enzymes produced by *Burkholderia sp*. KB7, providing novel insights into its targeted application in black pepper cultivation (Sidorova *et al.,* 2022). Moreover, open-field trials under diverse environmental conditions are essential to establish robust application protocols for varying climates (Glick *et al.,* 2020). To effectively manage large-scale applications, there is a need for innovative delivery methods, such as the use of seed coatings or bioformulations (Solano *et al.,* 2009).

CONCLUSION

This study underscores the remarkable potential of rhizobacteria as sustainable and eco-friendly biocontrol agents against *Phytophthora capsici*, a critical pathogen in black pepper cultivation. Out of 520 isolates collected from the rhizosphere soils of black pepper, ten demonstrated significant antagonistic properties, with isolate KB7 recording the highest inhibition rate of 87.59%. The biocontrol mechanisms identified include the production of antifungal enzymes such as chitinase, glucanase, and protease, as well as VOCs that effectively disrupted the structural integrity of fungal mycelia. These results underscore the crucial function of rhizobacteria, particularly *Burkholderia sp*. KB7, in the realm of integrated disease management, where they effectively inhibit pathogen development and foster the well-being of plants. Biosafety evaluations confirmed the safety of eight isolates for agricultural applications, as they were non-hemolytic and did not induce hypersensitive reactions. Molecular analysis

further classified isolate KB7 as *Burkholderia sp*., a genus widely recognized for its dual function as a plant growth-promoting bacterium and an effective biological control agent. The efficacy of *Burkholderia sp*. KB7 was validated through greenhouse trials, where it significantly reduced the incidence and severity of foot rot disease in black pepper plants. The results indicate a practical alternative to chemical fungicides, whose extensive application is commonly connected to soil deterioration, water contamination, and harmful effects on non-target organisms. By reducing dependence on synthetic pesticides, the deployment of rhizobacteria such as *Burkholderia sp*. KB7 can mitigate chemical runoff into ecosystems, protect biodiversity, and help maintain ecological balance. Furthermore, the use of biocontrol agents within agricultural systems plays a significant role in soil restoration, as it enhances microbial diversity, promotes nutrient cycling, and increases overall soil fertility. The application of *Burkholderia sp*. KB7 as a biocontrol agent aligns with global sustainability goals, such as reducing greenhouse gas emissions and the carbon footprint associated with intensive farming. By leveraging the natural antifungal and plant growth-promoting properties of rhizobacteria, this study advances the scientific understanding of biological disease control and provides a practical framework for improving agricultural sustainability and resilience against climate change. *Burkholderia sp*. KB7 stands out as a promising candidate for further exploration in agricultural biotechnology due to its dual advantages of promoting plant growth and enhancing disease resistance. This study not only contributes to the growing body of knowledge on biological control mechanisms but also underscores the urgency of integrating eco-friendly solutions into modern farming practices. Utilizing biologically derived alternatives in place of chemical inputs can significantly lessen environmental pollution, bolster the sustainability of farming systems, and respond to the rising demand for sustainable agricultural methods. In conclusion, the findings of this research emphasize the transformative potential of rhizobacteria, particularly *Burkholderia sp*. KB7, in fostering a future of resilient, eco-conscious, and productive agriculture, ensuring long-term food security and environmental health.

CHALLENGES AND FUTURE DIRECTIONS FOR FIELD APPLICATION

This discussion will focus on the challenges of sustaining bacterial viability in varying soil conditions, ensuring cost-efficient large-scale production, and adapting application methods to a range of field environments. Proposed solutions to these challenges will also be presented (Glick, 2018). Developing slow-release formulations and farmer training programs can address challenges in scaling up Burkholderia applications (Tariq *et al.,* 2020).

AUTHOR CONTRIBUTIONS

Sukamto performed the literature review, conceptualized the central research idea, designed the study, conduct the experiment, and manuscript preparation. Supriadi performed the literature review, conceptualized the central research idea, designed the study, and analyzed and interpreted the data. K.D. Sutanto Performed the literature review, analyzed and interpreted the data, manuscript preparation and helped in improvement of the manuscript. S. Hardiyanti performed the literature review and contributed to manuscript preparation. S.R. Djiwanti Performed helped in improvement of the manuscript. Wiratno Performed helped in improvement of the manuscript. D. Manohara Performed helped in improvement of the manuscript. R. Noveriza performed Analyzed and interpreted data and helped in preparing the manuscript text. W. Amaria performed in Administrative, technical support, manuscript edition and helped in improvement of the manuscript. R. Harni performed in Administrative, technical support, manuscript edition and helped in improvement of the manuscript. I.B. Rahardjo performed in Administrative, technical support, manuscript edition and helped in improvement of the manuscript.

ACKNOWLEDGEMENT

The authors would like to express their gratitude for the outstanding research support received by Indonesian Institute for Standard Testing of Spice and Medicinal Crops, Indonesia Center for Standard Testing of Estate Crops, Indonesian Agency for Agricultural Instrument Standardization, Ministry of Agriculture.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
16S rRNA	Subunit ribosomal Rinonucleic acid
ACC	1-Aminocyclopropane-1-carboxylate
ANOVA	Analysis of variance
B-KB1	Bhulkolderia isolate 1 collected from Bangka city with Kings B base media
B-ACT1	Bhulkolderia isolate 1 collected from Bangka city with actinomycetes media
BLAST	Basic local alignment search tool
Bnk	Bangka city
CFU/mL	Colony forming unit per milliliter
cm	Centimeter
Cryo-FESEM	Cryo-field emission scanning electron microscopy
DMRT	Duncan's multiple range test
g	Gram
IAA	Indole-3-acetic acid
IISR	Indian institute of species research
HR	Hypersensitivity response
KH_2PO_4	Monopotassium phosphate
$MgSO_4$	Magnesium sulfate
mL	Milliliter
mm	Millimeter
NaCl	Sodium chloride
NCBI	National Center for Biotechnology Information
PDA	Potato dextrose agar
PnCBNS4	*Pipper nigrum* conserved binding site number 4
PnCBNS1	*Pipper nigrum* conserved binding site number 1
rDNA	Ribosomal deoxyribonucleic acid
rRNA	Ribosomal ribonucleic acid
SMA	Skim Milk Agar
SPA	Starch casein agar
SPSS	Statistical package for the social sciences
S-KB1	Bhulkolderia isolate 1 collected from Sukamulya with Kings B base media

S-ACT1	Bhulkolderia isolate 1 collected from Sukamulya with actinomycetes media
S-SPA1	Bhulkolderia isolate 1 collected from Sukamulya with sucrose peptone agar
VOC	Volatile organic compound

REFERENCES

Admassie, M.; González-Pérez, E.; Woldehawariat, Y.; Alemu, T., (2023). Screening of potential bacterial isolates against *Phytophthora capsici* and its plant growth-promoting effect on pepper plants. Physiol. Mol. Plant Pathol., 127: 102028 **(10 pages)**.

Amaria, W.; Sinaga, M.S.; Mutaqin, K.H.; Supriadi; Widodo., (2023). Hemolysis and hypersensitive tests ease culture collection management of antagonistic bacteria. J. Trop. Plant Pests Dis., 23(2): 24-30 **(7 pages).**

Aravind R.; Kumar, A.; Eapen, S.J.; Ramana, K.V., (2008). Endophytic bacterial flora in root and stem tissues of black pepper (*Piper nigrum* L.) genotype: isolation, identification and evaluation against *Phytophthora capsici*. Lett. Appl. Microbiol., 48: 58-64 **(7 pages).**

Bernabeu, P.R.; Pistorio, M.; Gonzalo, T.G.; Santos, P.E.; Galar, M.L.; Boiardi, J.L.; María, F.; Luna, M.F., (2015). Colonization and plant growth-promotion of tomato by *Burkholderia tropica*. Sci. Hortic., 191: 113-120 **(8 pages).**

Chakraborty, A.; DasGupta., CK.; Bhadury, P., (2020). Diversity of Betaproteobacteria revealed by novel primers suggests their role in arsenic cycling. Heliyon. 6(1): e03089 **(8 pages).**

Chandrasekaran, M.; Paramasivan, M.; Sahayarayan, J.J., (2022). Microbial volatile organic compounds: An alternative for chemical fertilizers in sustainable agriculture development. Microorganisms. 11(1): 42 **(18 pages)**.

Chauhan, P.; Sharma, N.; Tapwal, A.; Kumar, A.; Verma, G.S.; Meena, M.; Seth, C.S.; Swapnil, P., (2023). Soil Microbiome: Diversity, Benefits and Interactions with Plants. Sustainability J., 15(19): 14643 **(43 pages).**

Chen, Y.Y.; Chen, P.C.; Tsay, T.T., (2016). The biocontrol efficacy and antibiotic activity of Streptomyces plicatus on the oomycete *Phytophthora capsica*. Biol. Control. 98: 34-42 **(9 pages).**

Dimkić, I.; Janakiev, T.; Petrović, M.; Degrassi, G.; Fira, D., (2022). Plant-associated Bacillus and Pseudomonas antimicrobial activities in plant disease suppression via biological control mechanisms - A review. Physiol. Mol. Plant Pathol., 117: 01754 **(10 pages).**

Fatimah; Nur Aula, N.; Salsabila, S.; Ramly, Z.A.; Rose, S.Y.; Surtiningsih, T.; Nurhariyati, T., (2023). Exploration of phosphate solubilizing bacteria from mangrove soil of Lamongan, East Java, Indonesia. Biodersitas. 24(2): 1272-1278 **(7 pages).**

Fishal, E.M.M.; Meon, S.; Wong Mui Yun, W.M., (2010). Induction of Tolerance to Fusarium Wilt and Defense-Related Mechanisms in the Plantlets of Susceptible Berangan Banana Pre-Inoculated with *Pseudomonas sp*. (UPMP3) and *Burkholderia sp*. (UPMB3), Agric. Sci. China. 9(8): 1140-1149 **(10 pages).**

Giorgio, A.; De Stradis, A.; Lo Cantore, P.; Iacobellis, N.S., (2015). Biocide effects of volatile organic compounds produced by potential biocontrol rhizobacteria on *Sclerotinia sclerotiorum*. Front. Microbiol., 6: 1–13 **(13 pages).**

Glick, B., (2018). Soil Microbes and Sustainable Agriculture. Pedosphere J., 28(2): 167-169 **(3 pages)**.

Harish, S.; Parthasarathy, S.; Durgadevi, D.; Anandhi, K.; Raguchander, T., (2019). Plant growth-promoting rhizobacteria: harnessing its potential for sustainable plant disease management. Plant growth promoting Rhizobacteria for agricultural sustainability: From theory to practices, 151-187 **(37 pages)**.

Huang, Z.; Liu, B.; Yin, Y.; Liang, F.; Xie, D.; Han, T.; Liu, Y.; Yan, B.; Li, Q.; Huang, Y.; Liu, Q., (2021). Impact of biocontrol microbes on soil microbial diversity in ginger (*Zingiber officinale* Roscoe). Pest Manage Sci., 77(12): 5537-5546 **(10 pages)**.

Joe, S; Sarojini, S., (2017). An Efficient Method of Production of Colloidal Chitin for Enumeration of Chitinase Producing Bacteria. Mapana J. Sci., 16(4): 37-45 **(9 pages).**

Khatun, A., Farhana, T., Sabir, A. A., Islam, S. M. N., West, H. M., Rahman, M., & Islam, T. (2018). Pseudomonas and Burkholderia inhibit growth and asexual development of *Phytophthora capsici*. Zeitschrift fuer Naturforschung C., 73(3-4): 123-135 **(13 pages)**.

Kong, P.; Hong, C., (2020). Endophytic *Burkholderia sp*. SSG as a potential biofertilizer promoting boxwood growth. PeerJ. 16(8): e9547 **(13 pages).**

Kumar, H.R.C.; Dubey, R.C.; Maheshwari, D.K., (2017). Seed-coating fenugreek with Burkholderia rhizobacteria enhances yield in field trials and can combat Fusarium wilt. Rhizosphere. 3(1): 92-99 **(8 pages).**

Lamour, KH.; Stam, R.; Jupe, L.; Huitema, E., (2012). The oomycete broad-host-range pathogen *Phytophthora capsici*. Mol. Plant Pathol., 13(4): 329–337 **(9 pages).**

Martins, S.J.; Faria, A.F.; Pedroso, M.P.; Cunha, M.G.; Rocha, M.R.; Medeiros, F.H.V., (2019). Microbial volatiles organic compounds control anthracnose (*Colletotrichum lindemuthianum*) in common bean (Phaseolus vulgaris L.). Biol. Cont. 131: 36-42 **(7 pages).**

Munjal, V.; Nadakkakath, A.V.; Sheoran, N.; Kundu, A.; Venugopal, V.; Subaharan, K.; Rajamma, S.; Eapen, S.J.; Kumar, A., (2016). Genotyping and identification of broad spectrum antimicrobial volatiles in black

pepper root endophytic biocontrol agent, *Bacillus megaterium* BP17. Biol. Control. 92: 66-76 **(11 pages).**

Naveed, M.; Mitter, B.; Reichenauer, T.G.; Wieczorek, K.; Angela, S.A., (2014). Increased drought stress resilience of maize through endophytic colonization by *Burkholderia phytofirmans* PsJN and Enterobacter sp. FD17. Environ. Exp. Bot., 97: 30-39 **(10 pages).**

Nazli, F.; Najm, S.; Khan, Y.; Jamil, M.; Nadeem, M.; Ahmad, S.; Maqshoof, A., (2020). Soil Microbes and Plant Health. Book Chapter In book n book: Plant Disease Management Strategies for Sustainable Agriculture through Traditional and Modern Approaches. 111-135 **(25 pages)**.

Palaniappan, P.; Chauhan, P.S.; Saravanan, V.S.; Anandham, R.; Sa, T., (2010). Isolation and characterization of plant growth promoting endophytic bacterial isolates from root nodule of Lespedeza sp. Biol. Fertil. Soils. 46: 807-816 **(10 pages).**

Packeiser, H; Lim, C.; Balagurunathan, B.; Wu, J.; Zhao, H., (2013). An extremely simple and effective colony PCR procedure for bacteria, yeasts, and microalgae. Appl. Biochem. Biotechnol., 169: 695-700 **(6 pages).**

Pang, Z.; Shao, J.; Chen, L.; Lu, X.; Hu, J.; Qin, Z.; Liu, X., (2013). Resistance to the novel fungicide pyrimorph in *Phytophthora capsici*: risk assessment and detection of point mutations in CesA3 that confer resistance. PLoS One. 8(2): e56513 **(12 pages).**

Razdan, V.K.; Sabitha, M., (2009). Integrated disease management: Concepts and practices. Integrated Pest Management: Innovation-Development Process. (1): 369-389 **(21 pages)**.

Sabalpara, A.N.; Mahatma, L., (2019). Role of Microbes in Sustainable Agriculture. In: Peshin, R., Dhawan, A. (eds) Natural Resource Management: Ecological Perspectives. Sustainability Plant Crop Protect., 147–163 **(17 pages)**.

Safitri D.; Wiyono S.; Purbajanti, E.D. (2023). Potential of endophytic yeasts as biocontrol of *Phytophthora capsici*, causative agent of foot rot disease on black pepper. Biodiversitas. 24 (11): 5847-5853 **(97 pages).**

Sheji, C.; Renu, S.G.; Balaji, S.; Anandaraj, M., (2009). Ribosomal DNA analysis of three Phytophthora species occurring in India. Indian Phytopathol., 62 (2): 155-162 **(8 pages).**

Singh, H.; Jaiswal H.; Singh, S.; Tiwari, S.P.; Singh, B.; Katiyar, D., (2017). Antagonistic Compounds Producing Plant Growth Promoting Rhizobacteria: A Tool for Management of Plant Disease. J. Adv. Microbiol., 3 (4): 1-12 **(12 pages)**.

Sidorova, D.E.; Vladimir, A.P.; Darya, A.P.; Evgeniya, V.; Kupriyanova, N.; V.R.; Olga A.K.; Inessa, A.K. 2022. "The Effect of Volatile Organic Compounds on Different Organisms: Agrobacteria, Plants and Insects" Microorganisms. 10(1): 69 **(13 pages)**.

Solano, B.R.; Maicas, J.B.; Mañero, J.G., (2009). Biotechnology of the Rhizosphere. In: Recent Advances in Plant Biotechnology. Springer US, Boston, MA., 137-162 **(26 pages)**.

Suriany, E.; Akhsan, N.; Sopialena., (2021). Response of Pepper Seeds Affected by Root Rot Disease (*Phytophthora capsici*) Towards Application of Secondary Metabolites of *Trichoderma sp*. Haya Saudi J. Life Sci., 6(6): 113-129 **(17 pages).**

Szczech, M.; Shoda, M., (2005). The influence of Bacillus subtilis RB14-C on the development of *Rhizoctonia solani* and indigenous microorganisms in the soil. Canadian J. Microbiol., 51(5): 405-411 **(7 pages).**

Tariq, M.; Khan, A.; Asif, M.; Khan, F.; Ansari, T.; Shariq, M.; Siddiqui, M.A., (2020). Biological control: a sustainable and practical approach for plant disease management. Acta Agriculturae Scandinavica, Section B — Soil Plant Sci., 70(6): 507–524 **(18 pages)**.

Thampi, A.; Bhai, R.S., (2017). Rhizosphere actinobacteria or combating *Phytophthora capsici* and *Sclerotium rolfsii*, the major soil borne pathogens of black pepper (*Piper nigrum* L.). Biol. Control. 109: 1-13 **(13 pages).**

Toh, S.C.; Samuel, L; Awang, A.S.A.H., (2016). Screening for antifungal-producing bacteria from Piper nigrum plant against *Phytophthora capsici*. Int. Food Res. J., 23(6): 2616-2622 **(7 pages).**

Umadevi, P.; Anandaraj, M., (2017). Genotype specific host resistance for Phytophthora in black pepper (*Piper nigrum* L.). Physiol. Mol. Plant Pathol., 237-241 **(5 pages).**

Vandana, V.V.; Bhai, S.R.; Azeez, S., (2014). Biochemical defense responses of black pepper (Piper nigrum L.) lines to *Phytophthora capsici*. Physiological and Molecular Plant Pathol., 88: 18-27 **(10 pages).**

Wang, Y.; Duan, S.; Xu, J.; Long, Y.; Zhang, S.; Li, S.; Wu, L.; Zhang, Y., (2023). Comparison of the colonization ability of Burkholderia strain B23 in the citrus rhizoplane and rhizosphere and assessment of the underlying mechanisms using full-length 16S rDNA amplicon and metatranscriptomic analyses. Microb. Biotechnol., 16: 1657–1670 **(14 pages).**

Wigley, P., (1999). Characterisation of burkholderia cepacia from clinical and environmental origins. Open University (United Kingdom) **(24 pages)**.

Willems, A., (2006). The Taxonomy of Rhizobia: An Overview. Plant Soil. 287(1/2): 3–14 **(12 pages).**

Young, L.; Hameed, A.; Peng, S.Y.; Shan, Y.H.; Szu-Pei-Wu, S.P., (2013). Endophytic establishment of the soil isolate *Burkholderia sp*. CC-Al74 enhances growth and P-utilization rate in maize (*Zea mays* L.). Appl. Soil Ecol., 66: 40-47 **(8 pages).**

Zohara, F.; Akanda, M.A.M.; Paul, N.C.; Mahfuz, R.M.; Islam, M.T., (2016). Inhibitory effects of *Pseudomonas spp*. on plant pathogen *Phytophthora capsici* in vitro and in planta. Biocatal. Agric. Biotechnol., 5: 69-77 **(9 pages**).

AUTHOR (S) BIOSKETCHES

Sukamto, Ph.D., Senior researcher, Research Center for Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *Sukamto@brin.go.id*
- ORCID: 0000-0003-1861-8127
- Web of Science ResearcherID: NA
- Scopus Author ID: 5748306400
- Homepage: http://www.agri.tohoku.ac.jp/en/

Sutanto, K.D., Ph.D., Postdoctoral fellow, Research Center for Horticulture, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia
- Email: *koko006@brin.go.id*
- ORCID: 0000-0002-3605-4954
- Web of Science ResearcherID: NA
- Scopus Author ID: 55980814800
- Homepage: http://ksu.edu.sa/index.php/en/home

Supriadi, Ph.D., Professor, Senior researcher, Research Center for Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *supra045@brin.go.id*
- ORCID: 0000-0001-7159-0202
- Web of Science ResearcherID: NA
- Scopus Author ID: 57513733000
- Homepage: https://www.ipb.ac.id/beranda/

Noveriza, R., Ph.D., Senior researcher, Research Center for Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *rita012@brin.go.id*
- ORCID: 0000-0002-3087-7570
- Web of Science ResearcherID: NA
- Scopus Author ID: 57196435496
- Homepage: https://www.ipb.ac.id/beranda/

Wiratno, Ph.D., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *wiratno02@Yahoo.com*
- ORCID: 0000-0001-6286-3352
- Web of Science ResearcherID: NA
- Scopus Author ID: 53508154800
- Homepage: http://www.wur.nl/en/education-programmes/wageningen-university.htm

Manohara D., Ph.D., Senior Researcher, Research Center for Estate Crops, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *dyah024@brin.go.id*
- ORCID: 0000-0002-3036-0248
- Web of Science ResearcherID: NA
- Scopus Author ID: 57200728787
- Homepage: https://www.ipb.ac.id/beranda/

Harni, R., Ph.D., Senior researcher, Research Center for Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *rita014@yahoo.com*
- ORCID: 0009-0008-3758-5838
- Web of Science ResearcherID: NA
- Scopus Author ID: 57196435496
- Homepage: https://www.ipb.ac.id/beranda/

Djiwanti, S.R., Ph.D., Senior researcher, Research Center for Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *rrse002@brin.go.id*
- ORCID: 0009-0002-1465-4163
- Web of Science ResearcherID: NA
- Scopus Author ID: 6507827104
- Homepage: https://www.ipb.ac.id/beranda/

Hardiyanti, S., Junior researcher, Research Center for Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *siti097@brin.go.id*
- ORCID: 0000-0001-7715-7709
- Web of Science ResearcherID: NA
- Scopus Author ID: 574586319000
- Homepage: https://www.ipb.ac.id/beranda

AUTHOR (S) BIOSKETCHES

Amaria, W., Ph.D., Junior researcher, Research Center for Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *widi011@brin.go.id*
▪ ORCID: 0000-0002-0838-2002
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57214720499
▪ Homepage: https://www.ipb.ac.id/beranda/

Rahardjo, I.B., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *ib.rahardjo@gmail.com*
▪ ORCID: 0000-0002-2892-0234
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 55337789900
▪ Homepage: https://unsoed.ac.id/

HOW TO CITE THIS ARTICLE

Sukamto; Sutanto, K.D.; Noveriza, R.; Hardiyanti, S.; Djiwanti, S.R.; Wiratno; Manohara, D.; Rahardjo, I.B.; Harni, R; Amaria, W.; Supriadi, (2025). Eco-friendly biocontrol of Phytophthora capsici in black pepper (Piper nigrum) using Burkholderia species. Global J. Environ. Sci. Manage., 11(2): 443-460.

DOI: 10.22034/gjesm.2025.02.05

URL: https://www.gjesm.net/article_719260.html

Global J. Environ. Sci. Manage. 11(2): 461-480, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Spatial heterogeneity of marine debris distribution on a tropical remote island shoreline

D. Purnama[1,2], N.P. Zamani[2,3,*], D.G. Bengen[2], R. Saville[4], M.R. Cordova[5]

[1] *Marine Science Department, Bengkulu University, Jl. WR. Supratman Kandang Limun, Bengkulu 38371 Indonesia*

[2] *Department of Marine Science and Technology, Bogor Agricultural University, Jl. Agatis Kampus IPB Darmaga, Bogor, Jawa Barat 16680 Indonesia*

[3] *Center for Transdiciplinary and Sustainability Science, IPB University, Kampus Baranangsiang, Bogor, Indonesia*

[4] *Faculty of International Agriculture and Food Studies, Tokyo University of Agriculture, Setagaya Campus 1-1-1 Sakuragaoka, Setagaya-ku, Tokyo 156-8502, Japan*

[5] *Research Center for Oceanography, National Research and Innovation Agency, Indonesia*

ARTICLE INFO

Article History:
Received 16 September 2024
Revised 21 November 2024
Accepted 27 December 2024

Keywords:
Enggano
Indian Ocean
Marine debris (MD)
Plastic

ABSTRACT

BACKGROUND AND OBJECTIVES: Enggano Island is in the Indonesian Sea, bordering the Indian Ocean. Cross-border marine debris will be stranded in the coastal areas of this island. This study was carried out over a 12-month, from June 2021 to May 2022, to examine marine debris's spatial and temporal accumulation. This study intends to assess the degree of marine debris accumulation on Enggano Island's coast, given its location adjacent to the Indian Ocean.

METHODS: This study employed a survey approach and was performed at 10 different stations in the southeastern part of Enggano Island. The first sampling was carried out 30 days after cleaning, during the lowest tide at the full moon phase (28 ± 3 days), conducted over 12 months from June 2021 to May 2022 to represent four seasons. For each category of marine debris, the abundance was determined by evaluating both the number of items and their respective weights. The relationship between seasonal abundance and the average seasonal current speed was examined to evaluate the influence of currents on marine debris levels.

FINDINGS: The total marine debris collected in this study was 16,382 items with a cumulative weight of 24,826 grams. The average density of marine debris was determined to be 0.387 ± 0.006 items per square meter, and the corresponding average weight was 11.545 ± 0.146 grams per square meter. Plastic has the highest percentage of all square meter's categories in all locations and seasons, namely 91.55 percent to 92.54 percent. In all categories of macro-debris, the most prevalent types of debris are Styrofoam, plastic bottles, fragments of plastic rope or small nets, thin plastic wrapping, and Plastic cups. The Marine debris found during the cleaning was plastic bottles from China, Switzerland, Sri Lanka, India, the Maldives, Myanmar, Malaysia, Singapore, Thailand, the Philippines, Australia, Seychelles, and the Middle East, with an average percentage of Indonesian-brand bottles (58.12 percent), foreign-brand bottles (19.59 percent), and unrecognized brands (22.29 percent). Moreover, substantial discrepancies in the abundance and weight of marine debris were recorded between various locations and seasonal periods throughout the sampling.

CONCLUSION: The marine debris that washed ashore on Enggano Island during the 12-month observation period, from June 2021 to May 2022, showed significant spatiotemporal variations. Each season was affected by variations in marine debris accumulation across different stations, along with the direction and speed of the seasonal currents. Plastic is the category of marine debris with the highest percentage in all locations and seasons, specifically 91.55–92.54 percent. It is believed that global marine hydrodynamics significantly contributes to marine debris strandings, indicating a need for more in-depth studies to understand the impact of hydrodynamics on the sources and heights of these strandings, especially for debris outside Enggano Island.

DOI: 10.22034/gjesm.2025.02.06

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
99	6	2

*Corresponding Author:
Email: *neviaty@apps.ipb.ac.id*
Phone: +6281 2315 33242
ORCID: 0000-0002-3312-2333

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODCTION

Marine debris (MD) is the trash that enters or is released into the coastal or marine environment. Much like other pollutants, MD affects the habitat, ecological dynamics, and health of species, along with the ecosystems where it accumulates. If not carefully managed, any manufactured object that does not break down spontaneously in a matter of days or months has the potential to become MD. The majority of scrap materials consist of paper, wood, textiles, metal, glass, ceramics, rubber, and plastic (UNEP, 2005). Representing the most common type of MD, plastic waste is found in concentrations of 60 to 90 percent (%) along coastlines and almost 90 percent on both the surface and the ocean floor (Cózar *et al.,* 2014; Martin, 2013). According to estimates made by Jambeck *et al.* (2015) in 2010, between 4.8 and 12.7 million metric tons (MMT) of plastic waste - out of the 275 MMT produced in 192 coastal countries - entered the ocean. If the trend of trash generation continues without any advances in waste management, this quantity is predicted to rise to 14.8-16.3 MMT in 2016 and might reach 53-90 MMT in 2030 (Borrelle *et al.,* 2020). Low-middle-income (LMI) nations have set high aspirations for waste management, targeting a 50% recycling rate by 2030, a significant increase from the average of 21% recorded in 2016 (Borrelle *et al.,* 2020). By creating a National Action Plan (NAP) on Waste, Indonesia, one of the LMI nations, plans to cut waste by up to 70% by 2025 (Metadata Peraturan, 2018). The majority of plastic garbage originates from human activities (Woods *et al.,* 2019)., including fishing (Donohue, 2005; Unger and Harrison, 2016) and tourism (Hayati *et al.,* 2020; Kuo and Huang, 2014; Zhou *et al.,* 2011). In oceanic environments, plastic waste can be carried by surface currents, resulting in its distribution or concentration in certain locations (Zhang *et al.,* 2017). Even farther away from the actual source of the plastic debris, they can spread (Hardesty *et al.,* 2017). River estuaries, tides, waves, and currents are some of the elements that affect the amount of plastic that ends up on beaches, waterways, and sediments (Lo *et al.,* 2020; Zhang *et al.,* 2017). Seasonal variations play a crucial role in the accumulation of stranded marine debris, which can differ markedly in both spatial distribution and temporal patterns (Cheung *et al.,* 2016; Cordova *et al.,* 2022a; Mugilarasan *et al.,* 2021; Ryan and Perold, 2021; Suteja *et al.,* 2021; Thiel *et al.,* 2021). Plastic waste builds up in sediments (Mauludy *et al.,* 2019; Peng *et al.,* 2018; Sari Dewi *et al.,* 2015; Nakajima *et al.,* 2021), on the water's surface (Hammer *et al.,* 2012; Reisser *et al.,* 2015; Lebreton *et al.,* 2019; Rothäusler *et al.,* 2019; Takarina *et al.,* 2022), and along coastlines (Behera *et al.,* 2021; Cordova *et al.,* 2022a). According to a number of studies, MD contamination harms the sea's ecosystems and biota, among other things (Kumar *et al.,* 2021; Derraik 2002). For instance, large plastic trash can entangle biota in turtles (Colferai *et al.,* 2017; Petry *et al.,* 2001; Vélez-Rubio *et al.,* 2018; Wilcox *et al.,* 2018) and marine mammals (Baulch and Perry, 2014; Brentano and Petry, 2020; Nurhasanah *et al.,* 2024; Basri *et al.,* 2024). Marine life that consumes plastic debris can occasionally suffer fatal consequences from misperceived satiety, ruptured stomachs, or obstructions within the digestive tract (Jacobsen *et al.,* 2010). According to Prokić *et al.* (2019), contamination with plastic particles can harm organisms in a number of ways, including immune system dysfunction, oxidative balance, energy metabolism, neurological damage, and histological damage. Continuous observation of MD contamination in the oceans is essential, given its significant and widespread impact (Ondara *et al.,* 2021). There is a scarcity of studies focusing on the volume, distribution, and consequences of plastic in Indonesia. As of right now, reports of MD buildup on Sumatra's west coast have come from Padang and Aceh (Cordova *et al.,* 2022a), Banda Aceh's Krueng Aceh river estuary (Ondara *et al.,* 2021), and Bengkulu's Kualo Beaches (Johan *et al.,* 2020). Despite the substantial influx of plastic waste each year to the outlying islands of the Indian Ocean (IO), such as Enggano Island, there has been no research undertaken in these regions (Pattiaratchi *et al.,* 2022). Because seasonal variations will alter existing patterns, the seasons have an impact on the buildup and dispersion of garbage in the oceans and along the coast. The majority of the garbage that comes from the southern region of Indonesia will go westward into the Indian Ocean on ocean currents and monsoon winds, according to Purba *et al.* (2021). Furthermore, Rahmania *et al.* (2021) indicate that during the west monsoon, marine debris entering Banten Bay can disperse further beyond the bay into the Sunda Strait. According to the findings of Rizal *et al.* (2021), drifters from Cisadane 1 are likely to

be confined to the southern Sunda Strait during the southwest monsoon due to the influence of the South Java Current (SJC), whereas they will move westward towards Madagascar during the northeast monsoon. Additionally, the research from Alamsyah *et al.* (2022) shows that there are differences in the types and amounts of waste in the west and east monsoon in Bone Bay which are caused by differences in current patterns in each season. The island of Enggano boasts rich ecosystems comprising coral reefs, seagrasses, and mangroves, which serve as habitats for numerous marine species that hold economic importance. These natural resources are vital for the economic well-being of the 4,112 inhabitants of the island (BPS, 2022). This island is one of the outer islands in Indonesia and is situated in the Indian Ocean. Based on previous work by Purba *et al.* (2021), they have mentioned that most of the islands in outer Indonesia are affected by marine debris from the Indonesian seas and surrounding seas. This island also became a remote island due to its location but has high biodiversity, as is common with small islands in Indonesia with their mega biodiversity (Suyadi *et al.,* 2021). It is essential to shield these different ecosystems from the infiltration of harmful substances, including MD, which can adversely affect their health and stability. Protecting this ecosystem from being damaged by MD pollution is necessary since, until now, waste disposal by the community has only been burned, stockpiled, or left in the environment, including trash that has been washed up on the beach, because there is no landfill on Enggano Island. Monitoring and managing waste on Enggano Island can be the first step taken. For a duration of 12 months, the monthly accumulation rate of MD was evaluated, beginning with the first sampling that took place 30 days after the initial cleaning. The study's initial hypothesis is that the amount of MDs stranded on the beach is correlated with the season. During certain seasons there is a higher buildup of MD, which is influenced by current patterns. The second hypothesis suggests that the influx of debris originating from the sea outweighs that from the mainland. This study marks the first of its kind to take place on the outermost islands of Indonesia that border the Indian Ocean, given that prior studies focused on MD monitoring have solely been conducted along the west coast of Sumatra Island. The concentration and distribution of MD, as well as the possible sources of stranded MD deposited in the study area, can be determined with the use of the study's findings. In addition, it will provide the groundwork for MD management initiatives at the regional level. Because Enggano Island borders the Indian Ocean, the purpose of this study is to determine whether the amount of MD buildup on its shore is extremely high. In 2022, this investigation was conducted on Indonesia's Enggano Island.

MATERIALS AND METHOD

Study area

This study took place in the Enggano Island area, one of Indonesia's foremost inhabited islands, which administratively belongs to the North Bengkulu district, Bengkulu Province (Fig. 1). Enggano Island has the closest distance to South Bengkulu Regency, which is 60 miles and 90 nautical miles from Bengkulu City. Enggano Island, with a land area of ± 39,720 hectares (ha) and a coastline length of ± 112 kilometers (km), has a population of 4,112 people in 2022, spread across six villages with six different tribes (BPS, 2022). The sampling took place at ten designated sites along the northern beaches of Enggano Island, which are situated near residential zones and display varying beach characteristics as defined by the National Oceanic and Atmospheric Administration (NOAA). The selected sites met several criteria: they featured either sandy or pebbly coastlines, provided access throughout the year or seasonally depending on conditions, lacked breakwaters or piers that might interfere with local water circulation and the accumulation of marine debris (MD), extended at least 100 meters (m) in length parallel to the shoreline, and were not subject to cleaning operations (Lippiatt *et al.,* 2013).

Sampling and debris estimation

The initial step in sampling was to clean the beach area which was the sampling location. Several MD found during cleaning came from outside Indonesia, the brand, printed language, and country of manufacturing mentioned were used to determine the country of origin, and debris in the form of products that were not available in Indonesia was classified as debris originating from outside Indonesia (Jang *et al.,* 2014; Lee *et al.,* 2012). In cases where the product's origin is not clearly indicated, one can resort to using Google for tracking purposes by

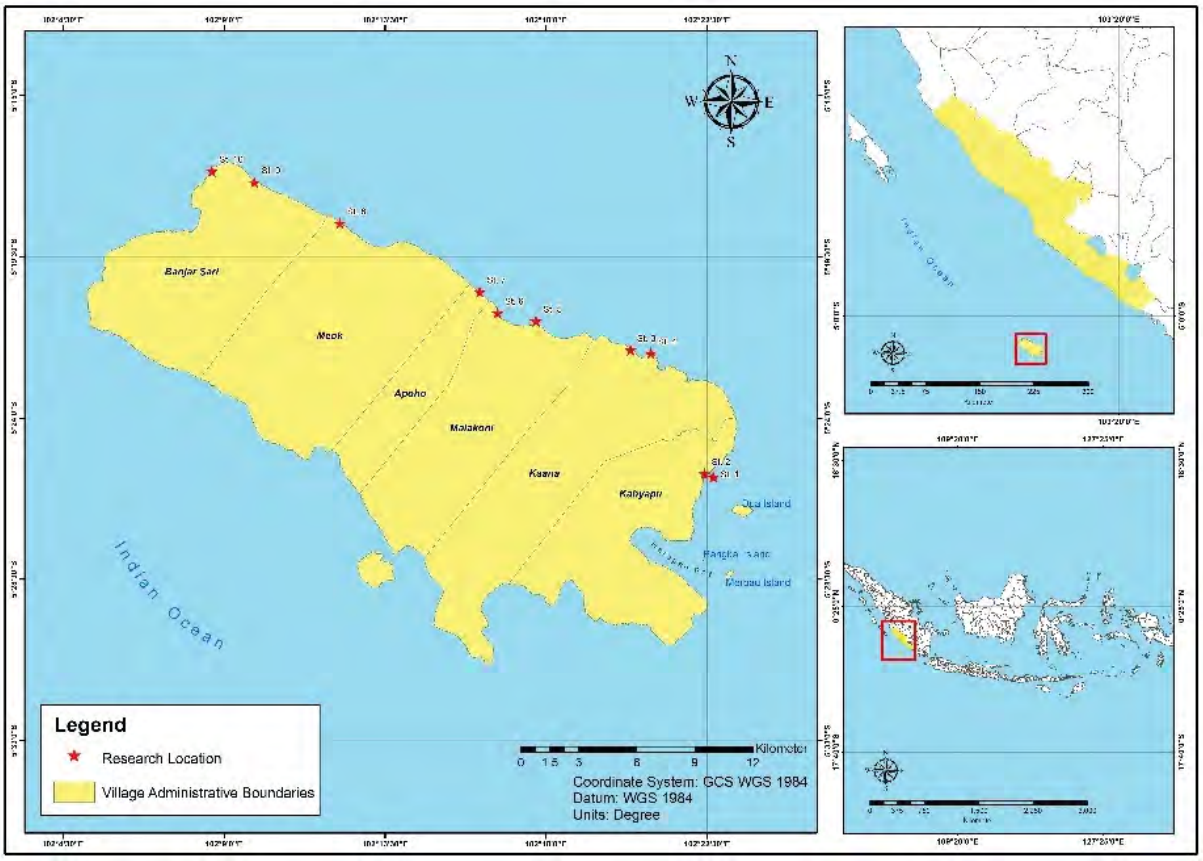


Fig. 1: Geographic location of the study area and sampling points in Enggano Island, Indonesia

analyzing the inscriptions on the bottle (bouwman *et al.,* 2016). After 30 days since the initial cleaning, MD samples were taken during the full moon every 28 (28 ± 3) days when the tide was low, between the highest and lowest tides to provide an accurate picture of the accumulation of plastic waste in that month. As noted by Lippiat *et al.* (2013), this sampling approach is effectively illustrating that collecting data at low tide during a full moon accurately reflects the amount of debris washed ashore during that month. The study was carried out over the course of one year to examine the seasonal representation. The 50 m line transect was divided into 2, with the width adjusted to the width of the beach at each sampling location so that the area of each location may be different. Each sampling location was equipped with Global positioning system (GPS) markers. The sampling process was conducted monthly, beginning in June 2021 and concluding in May 2022. MD that is collected and recorded must be at least 2.5 cm long, so it can be clearly visible and minimize the possibility of not being recorded. Debris that may be buried should be excavated and collected for recording. After being cleaned with water, the collected MD is wind-dried (slowly dried with air, away from direct sunlight) so that it can be visually identified, counted, and weighed using a digital scale (Digital Scales Harnic Heles HL-4350), maximum capacity of 5 kilograms (kg), accuracy of 0.1 gram (g), determined by the NOAA Program's categories, which include plastic and rubber, metal, glass, wood or paper, cloth, and others (Cordova and Nurhati, 2019; Lippiatt *et al.,* 2013). All identified MD types were employed to create distinct categories. Plastic and rubber were segmented into 13 sub-categories, whereas metal and fabric were each assigned one sub-category. Glass was categorized into two sub-categories, and processed wood was found only in certain sampling sites. Corpse/animal feces, leftover food, and unidentified waste are all classified as "other." Stranded MD density was calculated using

Eq. 1 (Cordova *et al.,* 2022a):

$$D = n / \omega \times l \quad (1)$$

Where,

D is debris density (items or weight per m^2); n is the item (number) or weight (g) of observed debris, ω is the transect width (m), and l is the transect length (m).

To determine the variation in abundance (number of items and weight) between seasons at each study location using statistical analysis non-parametric Kruskal Willis statistical test and Mann-Whitney paired post hoc test with a significant level of $p < 0.05$ using PAST (PAleontological STatistics) version 4.03 (PAST 4.03) for windows (Cordova *et al.,* 2022a; Hammer *et al.,* 2012). According to Triana *et al*. (2021) and Purba *et al*. (2021), seasonal changes are divided into three-month segments. They characterize the seasons as: the first transition or inter-monsoon period from March to May (MAM), the southeast monsoon from June to August (JJA), the second transition or inter-monsoon from September to November (SON), and the northwest monsoon from December to February (DJF).

The pattern of currents in four different seasons at the study location

The output model/monthly average data of current velocity in the direction-x (u) and the direction-y (v) in 2021 and 2022 of Enggano Island waters was downloaded from Copernicus Marine Service (CMS), taking into account the coordinates of the area, depth layer, time range, and the selected parameters. Subsequently, the data downloaded in the network common data form (netCDF) underwent additional processing software to derive average seasonal yields. In this study, the software used was PyFerret and ocean data view (ODV). The surface current system needs to be studied to see or predict the distribution of MD (Van Der Mheen *et al.,* 2020).

RESULTS AND DISCUSSION

The amount of MD during cleanup

In all observation stations, there were five sub-categories with the highest average number. The highest number of items was Styrofoam (0.138 ± 0.19 items/m^2), followed by plastic bottles (0.150 ± 0.25 items/m^2), plastic rope/small net piece (0.112 ± 0.19 items/m^2), thin plastic wrap (0.033 ± 0.03 items/m^2), and rope/fishing line/fishing rod (0.030 ± 0.03 items/m^2). The total MD collected at the time of cleaning from the 10 observation stations in this study was 2.268 items (5.77 tems/m^2), with a cumulative weight of 107,985.25 g as 274.65 grams per square meters (g/m^2). According to Table 1, the occurrence of plastic bottles is notably high at almost every station, with percentages falling between 11% and 32%. Station 10 is anticipated to exhibit the highest level, primarily due to the considerable volume of debris that has been stranded from the sea. In contrast, stations 1, 5, and 6 have a high percentage other than input from the sea, presumably because they are close to ports and fishery activities. The plastic rope/small net piece percentage is high at all stations except stations 1, 4, and 5. The greatest proportion of rope, fishing line, and fishing rods is observed at station 2, which can be attributed to its location near beaches that experience the most fishing activity. Conversely, Styrofoam was found in high amounts across all stations, except for station 2, where thin plastic wrap was the most abundant material. This Styrofoam mainly comes from fish storage boxes that are already in the form of fragments or shards. The percentage of debris weight differs from the percentage of the amount. For example, the weight percentage of plastic bottles is lower than the amount percentage at almost all stations because they weigh less. At stations 4 and 8, the weight percentage of rope, fishing line, and fishing rod is considerably greater than the total percentage, primarily because large net fishing gear was identified at these sites. This also holds true for apparel, shoes, sandals, and gloves; while the percentage may be lower, their weight percentage is significantly greater. Overall, it can be seen from the average percentage of MD at all stations (Table 1) that there are five sub-categories with the highest percentage. Styrofoam is the highest (23.41%), followed by plastic bottles (20.82%), plastic rope/small net piece (16.28%), thin plastic wrap (10.44%), and rope/fishing line/fishing rod (7.82%). While the average percentage of weight, there are six sub-categories, of which the highest is rope/fishing line/fishing rod (20.63%), followed by plastic bottles (13.48%), plastic rope/small net piece (13.38%), shoes/sandals/gloves (12.62%), glass bottles (12.27%), and Styrofoam (9.79%). The MD found during the cleaning included glass and plastic bottles originating from outside Enggano.

Table 1: Percentage of stranded MD during cleaning on Enggano Island from 22 categories based on abundance (A) and weight (W)

Category		I		II		III		IV		V		VI		VII		VIII		IX		X	
		A(%)	W(%)	A(%)	W(%)	A(%)	W(%)	A(%)	W(%)	A(%)	W(%)	A(%)	W(%)	A(%)	W %)	A(%)	W(%)	A(%)	W(%)	A(%)	W(%)
Plastic and Rubber	Ball, tire, balloon	0.46	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Plastic bottle	26.62	4.23	10.71	8.52	15.91	14.30	26.67	6.89	26.62	16.59	15.72	22.29	12.89	28.69	16.19	6.52	24.38	15.16	32.49	11.60
	Plastic cup	4.86	1.29	2.55	2.15	7.95	6.57	0.00	0.00	9.89	4.70	9.70	11.23	7.11	3.44	10.43	0.83	2.83	4.18	3.54	1.74
	Plastic cover	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.01	0.48	0.00	0.27	2.16	0.00	0.00	0.38	0.62	0.00
	Plastic match	0.00	0.00	2.04	0.73	1.14	0.24	10.00	3.49	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.29	0.00
	Thin plastic wrap	15.05	6.50	30.61	9.72	2.84	0.00	23.33	2.23	2.28	2.00	9.70	5.66	5.33	0.08	7.91	4.67	6.71	3.85	0.72	1.16
	Thick plastic wrap, sack	0.93	2.90	4.59	13.83	0.00	0.00	0.00	0.00	0.00	0.00	1.00	12.47	0.44	0.00	0.00	3.27	2.47	0.00	0.00	0.46
	Rubber band, rubber piece	0.69	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	1.06	0.00	0.00	0.00
	Straw	0.23	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.33	0.00	0.00	0.00	0.00	0.00	0.00	0.29
	Shoes, sandal, glove	3.94	8.62	2.55	2.24	9.09	23.48	0.00	0.00	10.27	22.23	5.35	0.00	12.44	23.17	8.63	8.09	5.30	19.87	8.33	18.55
	Styrofoam	17.13	2.53	1.02	1.25	29.55	10.19	26.67	4.46	33.27	10.36	15.05	12.21	32.44	13.98	14.03	9.50	39.93	14.14	25.02	19.29
	Rope, fishing line, fishing rod	11.57	22.69	24.49	19.32	9.09	5.93	13.33	82.93	7.60	5.80	5.02	4.95	0.00	2.57	0.00	62.09	5.30	0.00	1.82	0.00
	Plastic rope/small net piece	5.09	17.84	13.27	16.64	18.75	16.93	0.00	0.00	2.28	16.59	33.44	18.05	20.00	13.88	35.97	0.63	9.19	13.41	24.83	19.86
Metal	Can	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.00	1.00	4.07	0.89	0.00	1.08	0.00	0.00	2.34	0.00	0.31
Glass	Glass bottle	1.85	2.90	0.00	0.00	5.11	22.10	0.00	0.00	6.46	21.56	2.01	8.58	4.89	13.76	3.60	3.48	2.12	26.68	2.34	23.61
	Glass, broken glass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.16	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.57
Cloth/ Fiber	Clothes	11.57	29.60	8.16	25.60	0.57	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.84	0.71	0.00	0.00	2.56
Others	Others	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



Fig. 2: Foreign plastic bottles' brands found washed up on Enggano Island

The analysis of brand identity, language, and origin reveals that numerous bottles originate from China, Switzerland, Sri Lanka, India, the Maldives, Myanmar, Malaysia, Singapore, Thailand, the Philippines, Australia, Seychelles, and the Middle East (Fig. 2), with an average percentage of Indonesian brand bottles (58.12%), foreign brand bottles (19.59%), and unrecognized brand bottles (22.29%). No location at any sampling station has undergone cleaning, possibly due to the extensive buildup of debris from outside influences over the years. Brands from China, Indonesia, Thailand, India, Malaysia, Singapore, South Africa, and other countries were the source of MD on the Seychelles islands, according to a different study by Vogt-Vincent *et al.* (2023). The deposition of microplastics from remote areas, along with floating plastic debris, is affected by the monsoon winds, which integrate these materials into the regional current system. According to labels, the MD stranded on St. Brandon's Islands came from Malaysia, Thailand, and Indonesia, and it's possible that the South Equatorial Current of the Indian Ocean brought them to the archipelago, according to another study by Evans *et al.* (2011). Documentation reveals that most of the medical professionals who became stranded on the Little and Great Nicobar Islands were from adjacent nations, including China, Cuba, Indonesia, Malaysia, Myanmar, and Thailand rather than India (Das *et al.*, 2016).

Plastic has the highest percentage of all MD categories in all locations and seasons, namely 91.55% - 92.54%. Some MDs found are likely from ship traffic activities; in this study, MDs of drink bottles, both plastic and glass, with brands that may originate from cruise ships or ship waste in the past, were also found. As noted by Čulin and Bielić (2016), the origins of debris in marine environments include passenger ships, merchant ships, recreational vessels, commercial fishing boats, oil drilling platforms, and military vessels. Enggano itself is included in ALKI 1 (Indonesian Archipelagic Sea Channels). Despite the fact that ship debris disposal was forbidden by the 1988 International Convention for the Prevention of Pollution from Ships (MARPOL), it still occurs, one of which is through illegal disposal (Richardson *et al.*, 2021; Stelfox *et al.*, 2020). Historically, the primary source of plastic pollution in the oceans has been ships, which have a tradition of disposing of debris directly into the sea (Hagen, 1990). Furthermore, the MD material that washed up on the coast of Enggano Island might have been transported from different islands or countries, influenced by surface currents. According to Pattiaratchi *et al.* (2022), Van Der Mheen *et al*. (2020), and Purba *et al*. (2021), this current can

facilitate the movement of plastic waste to the Indian Ocean via the Indonesian Crossflow. Their research highlights that monsoon winds play a significant role in influencing the distribution of marine debris. Marine debris in the Sunda Strait expanded up to 938 kilometers to the west side of the strait and the Sumatra Island shore, according to the findings of tests conducted using GNOME (General NOAA Operational Modeling Environment). According to research by Akbar *et al*. (2022), which employed the same approach, the movement of waste is influenced by seasonal current patterns. Rizal *et al.* (2021) reported that the results of marine debris tracking by the mobidrift client portal (MDC) on the Cisadane 01 drifter were detected moving westward out of Indonesian territory, after floating on the ocean for over a year, they arrived at the east coast of Africa. According to research by Kisnarti *et al*. (2021), marine debris originating from six coastal cities was tracked using a trajectory model and a numerical model developed with the Hamburg Shelf Ocean Model (HAMSOM). The study demonstrated that these particles moved with ocean currents, dispersing to regions around the source of the waste and even reaching areas outside of Indonesian territorial waters. Duncan *et al.* (2020) reported that the movement of single pieces of plastic waste as 500 milliliters (mL) bottles of polyethylene terephthalate beverages) via the Ganges River system into the marine system Bay of Bengal was a 2,845 km maximum distance for 94 days. Cordova *et al.* (2022a) stated that many macro-debris objects remain afloat after They can travel great distances with ease and penetrate aquatic environments. The movement of ocean currents has led to the delivery of marine debris to the islands, where the south monsoon current (SEM) has contributed to the entrapment of debris in the Cocos (Keeling) Islands (Lavers *et al.,* 2019). Krishnakumar *et al.* (2020) argued that debris disposed of might be swept away by currents in the maritime environment, which would then circle the island before arriving in the Andaman and Nicobar Islands' coastal regions. he prevailing monsoon circulation will cause variations in surface currents (Sprintall *et al.,* 2009). Across all sampling locations, the marine debris found on the shores of Enggano Island is predominantly made up of plastic materials. This includes plastic bottles, lightweight plastic wraps, fragments of plastic ropes and nets, Styrofoam, and various fishing gear like ropes and lines (Fig. 3). Plastic bottles and thin plastic wrap probably originated from land as debris from daily human activities and from the sea as stranded debris. These types of plastic have high buoyancy and are widely used as disposable food and beverage packaging. From 12 billion in 2000 to 36 billion in 2006, the amount of waste produced by plastic bottles is substantial and still rising (Ajaj *et al.,* 2022). For instance, PET water bottles are commonly used in the United Arab Emirates (UAE), where each person may use up to 450 bottles of water year. In contrast, water bottles made of polyethylene terephthalate (PET) are a huge waste and have a considerable carbon footprint (Ajaj *et al.,* 2022). The elevated levels of Styrofoam and fishing gear, including rope and fishing line, are probably a result of fishing activities, as Styrofoam is commonly utilized by fishermen to store their catches. When it is damaged and cannot be used, it will be thrown into the sea and washed up on the coast as fragments or debris. In studies focused on the abundance, distribution, and sources of microplastics in the northern regions of the South China Sea, polystyrene emerges as the most frequently encountered material (Zhou *et al.,* 2011). One way that MD enters marine waters is through fishing operations (Donohue, 2005; Sinopoli *et al.,* 2020; Unger and Harrison, 2016). According to the results of research by Pauly and Zeller (2016), around 13% of global marine fishing comes from the IO region, this makes it a major contributor to the plastic waste in IO. One of the main causes of plastic trash at sea is fishing industry-related abandoned, lost, and discarded fishing gear (ALDFG) (Lebreton *et al.,* 2022; Richardson *et al.,* 2021), washes up on the coast (Behera *et al.,* 2021; Cordova *et al.,* 2022a; Thiel *et al.,* 2021; Unger and Harrison, 2016), and impacts marine biota (Jacobsen *et al.,* 2010). ALDFG is a significant contributor to MD in the sea and harms the ecology and socio-economics of coastal and near-shore areas (Gilman *et al.,* 2021; Macfadyen *et al.,* 2009). Gilman *et al.* (2022) worked to create the most suitable and promising ALDFG mitigation strategies and priorities in order to enhance fisheries management to reduce the component of global MD originating from ALDFG. Moreover, pieces of plastic rope and small nets constitute debris originating from larger marine plastic debris (MPD) that has harmed the environment. Sunlight mechanically degrades these plastic products into smaller fragments

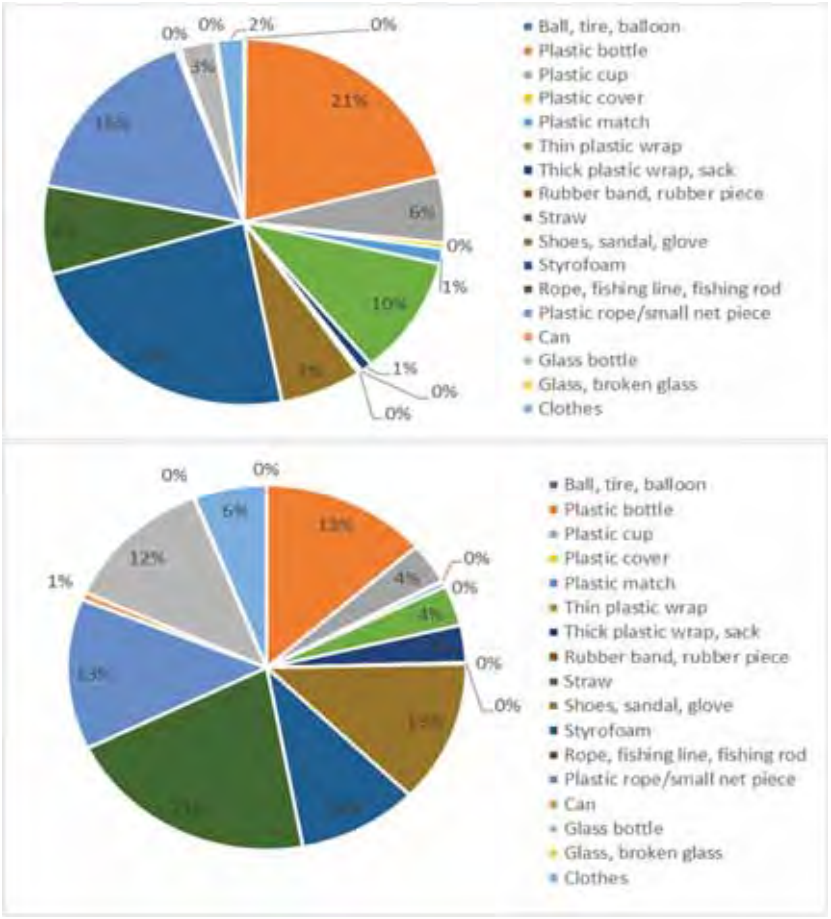


Fig. 3: Percentage of total abundance (top) and weight (bottom) of stranded MD during cleaning at Enggano Island

(Mrosovsky *et al.,* 2009). According to Costa *et al.* (2010), The breakdown of bigger plastics is the main source of fragments (96.7%), and many of these are discovered washed up on the coast (Ivar do Sul and Costa, 2007). A significant portion of the plastic waste located on Enggano Island's coastline has been reduced to small fragments, which complicates the identification of their initial use (Thiel *et al.,* 2021). Overall, the percentage of MD abundance in some of the sub-categories was lower than the weight percentage, possibly because of several sub-categories. However, the number is smaller and has a higher weight, such as rope/fishing line/fishing rod, clothes, and shoes/sandals/gloves (Fig. 3).

Seasonal density of stranded MD

Seasonal factors played a significant role in determining the weight and abundance observed during the survey. Throughout the 12-month sampling period, 16,382 items were gathered from 10 different stations, accumulating to a total weight of 24,826 grams. The average MD abundance during the study was 0.387 ± 0.006 item/m^2, and the average weight was 11.545 ± 0.146 g/m^2. MD abundance during the JJA season ranged from 0.060–0.188 item/m^2, with an average of 0.106 ± 0.008 item/m^2. The SON season were ranging from 0.053–0.248 item/m^2, with an average of 0.107 ± 0.008 item/m^2. The DJF season ranges from 0.027–0.185 item/m^2, with an average of 0.082 ± 0.006 item/m^2. The MAM ranges from 0.029–0.183 item/m^2 with an average of 0.084 ± 0.007 item/m^2 (Fig. 4). Meanwhile, the MD weight during the JJA season ranges from 0.586–14.629 g/m^2 with an average of 4.167 ± 0.326 g/m^2. The SON ranges from 1.193–7.878 g/m^2, with an average of 3.038 ± 0.265 g/m^2. The DJF ranges from 0.711–3.294 g/m^2, with

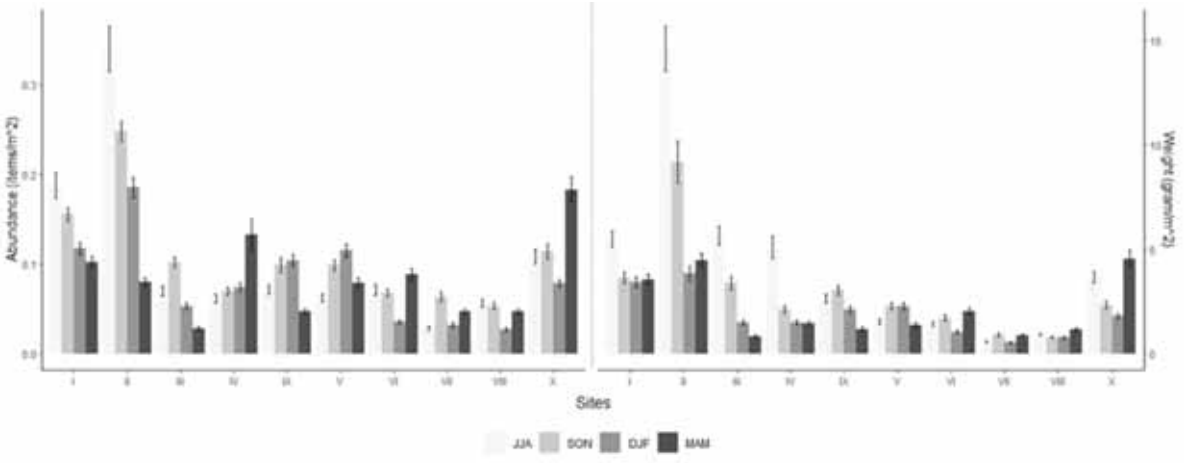


Fig. 4: Marine debris based on abundance (left) and weight (right) in 4 different seasons

an average of 2.013 ± 0.144 g/m^2. The MAM ranges from 0.711–5.205 g/m^2, with an average of 2.290 ± 0.172 g/m^2 (Fig. 4). Analysis using non-parametric statistical tests, specifically the Kruskal-Wallis test, demonstrated that there were significant differences in MD abundances and weights among the various sampling locations.

The JJA data indicates that stations 2 and 1 exhibit the highest levels of MD, recorded at 0.291 item/m2 and 0.161 item/m2, respectively. This pattern is thought to arise from the irregular currents during the southeast monsoon, which differ spatially between the Sumatra coast and Enggano Island, primarily moving in a westward direction. In the DJF, the highest ones are stations 2, 1, 4, and 9 (0.185 item/m^2, 0.118 item/m^2, 0.115 item/m^2, and 0.104 item/m^2, respectively), where the current tends to move from northwest to southeast, with the low current speed at the north area of Enggano Island along the coast of Sumatra. In MAM, the highest abundance was at stations 10 and 4 (0.183 item/m^2 and 0.132 item/m^2, respectively), which tended to have stronger currents than the other seasons from the northwest to the southeast, similar to the pattern of the western monsoon currents. In transition season 2 (SON), the current pattern is almost the same as the southeast monsoon, where the highest abundance is at stations 2, 1, 10, 9, and 4 (0.213 items/m^2, 0.133 items/m^2, 0.130 items/m^2, 0.127 items /m^2, 0.127 items/m^2, respectively). Conversely, stations 5, 6, 7, and 8 show little variation and tend to have lower measurements than other stations, presumably because they are situated on the island's side with a weaker current. Surface currents are anticipated to fluctuate in accordance with the prevailing monsoon patterns (Sprintall *et al.,* 2009). The variations in weight across seasons at each station correspond with the abundance levels. Generally, the seasonal current dynamics in the waters off Enggano Island are consistent with the wind direction patterns (Fig. 5), and surface currents are influenced by wind speed and direction (Wyrtki, 1961).

Findings from the study reveal that a considerable proportion of the debris that accumulates on beaches is plastic, and the minimal presence of non-floating materials like glass or metal is generally seen as an indication that the debris comes from marine sources (Honorato-Zimmer *et al*., 2019). Research conducted by Krishnakumar et al. (2020) in the Andaman and Nicobar Islands and by Lavers *et al*. (2019) in the Cocos (Keeling) Islands analyzed debris that has been washed ashore by ocean. Various studies have proven that currents transport MPD to the islands (Lavers *et al.,* 2019; Pattiaratchi *et al.,* 2022; Suteja *et al.,* 2021; Thiel *et al.,* 2021; Van Der Mheen *et al.,* 2020). According to the results of research by Blickley *et al.* (2016), the trade northeast wind plays an important role in the disposition of debris on the coast of Maui rather than in proximity to urban areas. Moreover, according to Ourmieres et al. (2018), the interplay of coastal currents and onshore winds in the northern Mediterranean Sea affected the gathering and distribution of floating marine debris, leading to its deposition along the coastline

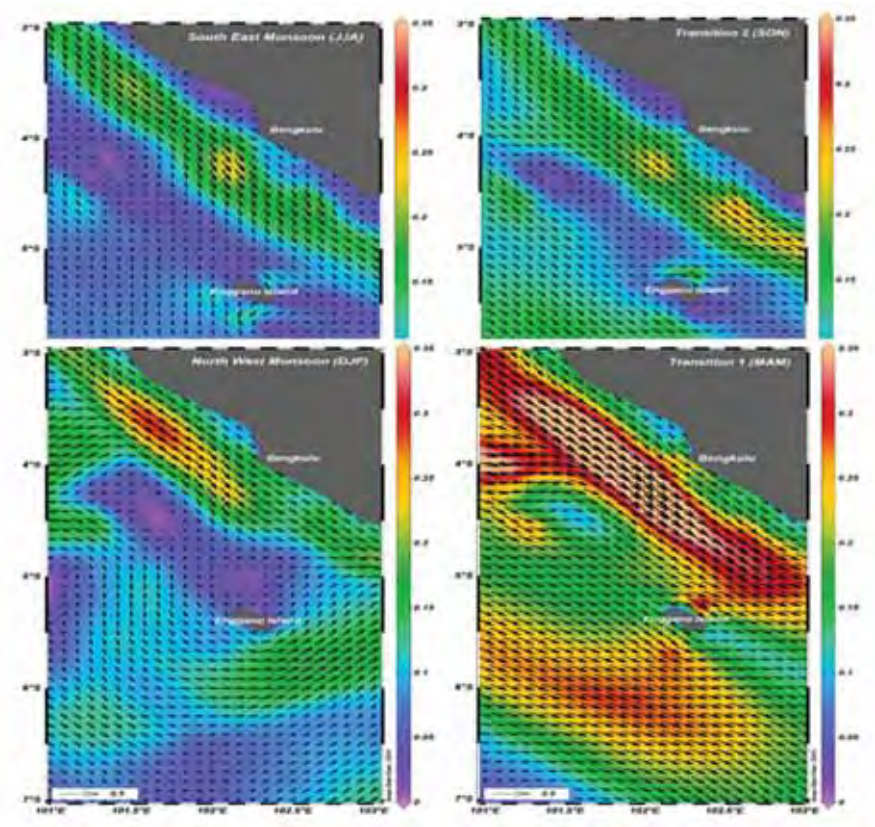


Fig. 5: Seasonal current patterns on Enggano Island

of Antibes in France. Changes in wind direction due to monsoon wind reversal, fronts, and upwelling, for example, are particularly important for IO, oceanography, and topographic features that control the distribution of plastic. The plastic that washes up on the island's coast in IO comes from the sea; the detection using optical remote sensing proves that the concentration of MPD on the beach is a result of deposition from marine sources (Guffogg *et al.,* 2021). Projections indicate that a significant portion of the floating plastic is likely to end up on the shores of the northern Indian Ocean, as the presence of land inhibits the development of a subtropical gyre in that area (Pattiaratchi *et al.,* 2022). Debris dynamics in subtropical gyres and buildup on oceanic islands can potentially be impacted by seasonal or interannual changes in large-scale oceanography (Blickley *et al.,* 2016; Morishige *et al.,* 2007). Analysis using non-parametric statistical methods revealed significant differences in both the abundance and weight of stranded MDs on Enggano Island between seasons. This result is in line with that reported by Cordova *et al.* (2022a), where the abundance and weight of MD differed significantly between the rainy and dry seasons over 12 months of sampling at 18 beaches in Indonesia. Likewise, the results of research by Suteja *et al.* (2021) in Bali vary significantly between seasons. Ryan and Perold (2021) found that the load of trash on the beach peaked during rain events and decreased after rain events in Cape Town, South Africa. Unlike the situation on the Maui shore, where debris accumulation remains consistent throughout the year, these outcomes present a different trend (Blickley *et al.,* 2016). Cheung *et al.* (2016) reported that there is no difference in abundance and weight between seasons; The Pearl River Estuary, situated in the western part of the city, plays a crucial role in shaping the quantity and distribution of plastic waste in Hong Kong.

Seasonal category of MD

In every season across all sampling stations,

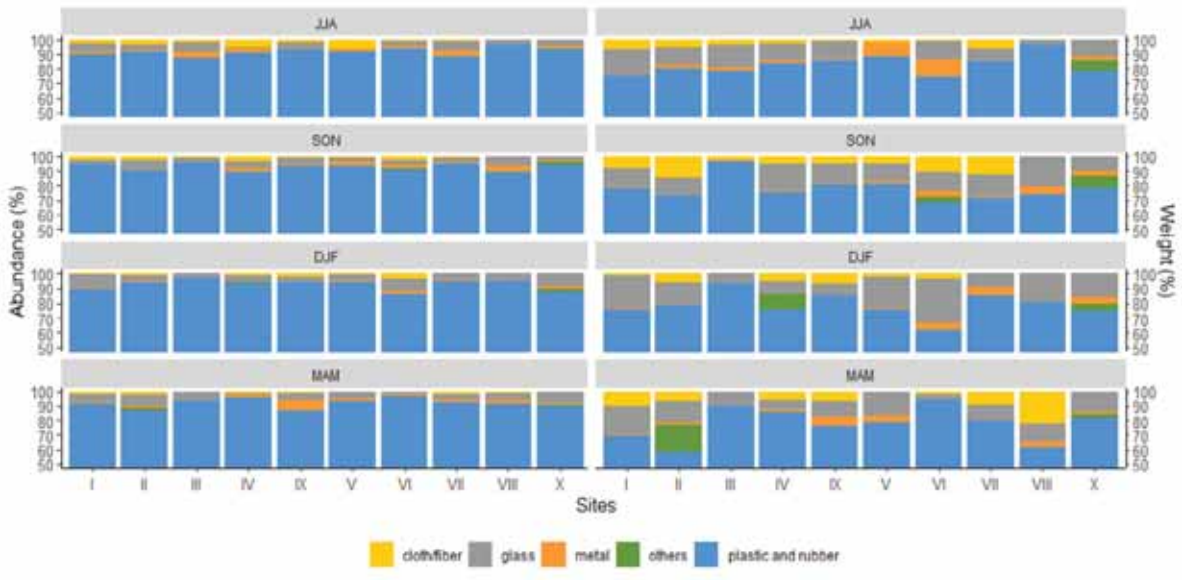


Fig. 6: Percentage marine debris category based on abundance (left panels) and weight (right panels) in 4 different seasons

plastic made up the highest percentage in terms of both abundance and weight. The percentage of the abundance of plastic, metal, glass, clothing, and others in JJA is 91.55%, 1.93%, 4.06%, 2.47%, and 0%. The SON is 92.54%, 1.71%, 4.08%, 1.52%, and 0.15%. The DJF is 92.21%, 0.86%, 5.67%, 1.18%, and 0.06%. The MAM is 91.80%, 2.11%, 4.96%, 1.00%, and 0.12%. Each category's percentage value differs in weight, indicating that even a limited abundance can possess a higher level of importance. The weight percentage of plastic, metal, glass, clothing, and others in JJA is 80.82%, 3.64%, 11.53%, 4.02%, and 0%. The SON is 77.69%, 1.73%, 12.96%, 7.18%, and 0.44%. The DJF is 78.46%, 1.60%, 15.89%, 3.07%, and 0.98%. The MAM was 77.55%, 2.31%, 11.78%, 6.47%, and 1.89% (Fig. 6). The analysis of stranded marine debris revealed that the plastic category comprised five sub-categories with the greatest abundance percentages in JJA. These were pipes, hoses, and pieces, which accounted for 21.27%; Styrofoams at 18.31%; plastic bottles at 14.01%; thin plastic wraps at 12.90%; and plastic cups at 9.64%. In the SON period, the composition of materials is as follows: pipes, hoses, and pieces account for 20.39%; Styrofoams make up 14.58%; plastic bottles represent 14.29%; plastic cups are at 12.89%; and thin plastic wraps are at 9.35%. In contrast, during DJF, the percentages change to 24.24% for pipes, hoses, and pieces; 19.12% for plastic bottles; 14.41% for Styrofoams; 11.46% for plastic cups; and 5.45% for thin plastic wraps. In MAM, plastic bottles dominate at 27.70%, followed by Styrofoams at 17.95%; plastic cups at 13.38%; pipes, hoses, and pieces at 12.00%; and thin plastic wraps at 5.81%. In terms of weight percentage, the plastic category contributing most to the glass bottle sub-category at JJA included Styrofoams at 13.77%, followed closely by plastic bottles at 13.66%, and pipes, hoses, and pieces at 13.56%. Other notable contributions came from shoes, sandals, and gloves at 9.92%, plastic cups at 8.74%, thin plastic wrap at 8.13%, and the glass bottle sub-category itself at 8.74%. In SON, the leading contributors were Styrofoams at 16.12%, plastic bottles at 15.02%, and pipes, hoses, and pieces at 10.86%. Additional contributions included plastic cups at 8.56%, thin plastic wraps at 7.30%, and the glass bottle sub-category at 9.50%. During DJF, the plastic sub-category saw plastic bottles at 19.28%, shoes, sandals, and gloves at 12.18%, and Styrofoams at 12.02%. Other contributions included pipes, hoses, and pieces at 10.17%, ropes, fishing lines, and fishing rods at 7.89%, and the glass bottle sub-category at 12.95%. In MAM, the plastic sub-category was led by plastic bottles at 21.15%, followed by shoes, sandals, and gloves at 14.20%, and Styrofoams at 12.42%. Additional contributions were from plastic cups at 7.11% and the glass bottle sub-category at 10.12%.

Statistically, the MD category stranded on the south coast of Enggano Island exhibited significant differences between the median samples.

The findings of this study reveal that plastic debris constitutes the majority of the waste observed, with its prevalence matching or possibly surpassing the findings from other investigations conducted on coastal areas and the small islands of IO (Table 2). This fact is not surprising, considering that plastic is the most common product used by humans, and debris is increasing exponentially in the world's oceans, including in IO (Borrelle *et al.,* 2020; Pattiaratchi *et al.,* 2022) estimate that 19–23 MMT, or 11%, of plastic debris generated globally in 2016 entered aquatic ecosystems. The results of calculations reinforce this statement by Jambeck *et al.* (2015): In 2010, 192 coastal countries produced 275 MMT of plastic trash, of which 4.8 to 12.7 MMT ended up in the oceans.

Table 2: Comparison of stranded MD with other previous studies in IO

Observation sites	Country	Sampling periods	Number of items	Major debris	Sources
Small island/remote island					
The Chagos Archipelago	Inggris territory	Diego Garcia Atoll: October–November 2021 Egmont Atoll: June–July 2022	136.3 bottles per 100 m transect	-	Savage *et al.,* 2024
St Brandon's Islands	Republik Mauritius	16 – 19 October 2017	25,992 items, over a total distance of 7.2 km	Plastic and plasticised paper (> 50%)	Evans *et al.,* 2011
little and Great Nicobar Islands	India	February to March 2016			
Nallathanni Island	India	16 – 19 October 2017	-	Plastic (86.5%)	Krishnakuma *et al.,* 2018
Andaman and Nicobar Island	India	-	Andaman: Macro – 358 Particles; Meso – 135; Micro – 125 Particles Nircobar: Macro – 925; Meso – 265; Micro – 88 Particles	-	Krishnakuma *et al.,* 2018
Cocos (Keeling) Island	Australia	2017	23,227 items	Plastic (95.41%)	Lavers *et al.,* 2019
Beaches					
Gulf of Mannar	India	February 2018 and March 2019	-	Fishing nets 43.17 ± 5.48%	Patterson Edward *et al.,* 2020
Ampasindava beaches	Madagascar	10 – 23 April 2015	0.158 item/m^2	Plastic (62.34%)5	Gjerdseth, 2017
Alphonse Island	Republic Seychelles	21 June to 2 August 2013	4.743 items/m^2	Plastic (96%)	Duhec *et al.,* 2015
Sri Lanka beaches	Sri Lanka	2016	4.1–158 item/m^2	Plastic (93.3 %)	Jang *et al.,* 2018
Indian north east beaches	India	2018	0.98 ± 0.34 item/m^2	Plastic (84.6 %)	Mugilarasan *et al.,* 2021
Karnataka Beaches	India	October -December 2005	-	Food-based plastics (43%)	Sridhar and Bhat, 2009
Mumbai beaches	India	May 2011 to March 2012	68.83 items/m^2	Fractionation of plastics (41.85%)	Jayasiri *et al.,* 2013
Padang and Aceh	Indonesia	February 2018 to December 2019	Padang: 9.31 ± 0.46 items/m2 Aceh: 5.3 items/m2	Macroplastics (46.3%)	Cordova *et al.,* 2022b
Kualo beaches Bengkulu	Indonesia	August 2019 to January 2020	0.28 – 0.9 items/m2	Plastic (86.66%)	Johan *et al.,* 2020
Enggano Island	Indonesia	June 2021 – May 2022	0.387 ± 0.006 item/m^2	Plastic (91.55% - 92.54%)	The current study

Approximately 9% of the 6,300 MMT of plastic waste produced in 2015 was recycled, 12% was burned, and 79% ended up in landfills or the environment. Should the existing patterns of garbage generation and management remain unchanged, it is estimated that by the year 2050, approximately 12,000 million metric tons of plastic waste will be found in landfills or dispersed throughout the environment (Geyer *et al.,* 2017). In general, the most prevalent kinds of plastic discovered over the 12-month sampling period were the same as when cleaning the beach prior to the monthly sampling: plastic bottles, thin plastic wrap, plastic rope/small net pieces, Styrofoam, and rope/fishing line/fishing rod. As noted by Geyer *et al*. (2017), single-use plastic packaging represents the predominant market for plastics. The majority of this packaging is utilized in the same year it is manufactured, leading to a much higher level of waste generation in the environment from plastic packaging than from construction-related plastics. If this accumulation of MD continues, it will threaten the sustainability and diversity of biodiversity and ecosystems (Kumar *et al.,* 2021). Even though Enggano is one of Indonesia's leading islands, the sustainability of coastal ecosystems is crucial.

Implications and opportunities for work in the future

The findings of this study reveal that plastic constitutes the majority of marine debris on Enggano Island. During the first phase of cleanup, plastic bottles from multiple nations outside of Indonesia were discovered. The entry of MD into the remote island and its accumulation over the years is due to the absence of any previous beach cleaning activities. Several types of unidentified bottles were located, potentially as a result of being discarded long ago or having spent a significant amount of time adrift. Various studies have proven that local and regional currents play a significant role in the dispersion of marine debris in the ocean, leading to its stranding on coastlines and small islands far from the mainland. The entry of MD into the Indian Ocean is closely related to the Indonesian Throughflow, monsoon winds, and current system (Sprintall *et al.,* 2009; Evans *et al.,* 2011; Lavers *et al.,* 2019; Krishnakumar *et al.,* 2020; Van Der Mheen *et al.,* 2020; Purba *et al.,* 2021; Rahmania *et al.,* 2021; Rizal *et al.,* 2021; Alamsyah *et al.,* 2022; Pattiaratchi *et al.,* 2022). Despite the existing limitations in knowledge and funding available to researchers, further investigation into the impact of currents on the distribution and deposition of microplastics has not been pursued. Collaboration is needed for further research to understand the impact of hydrodynamics. Various modeling can be used to estimate this, such as using GNOME, MDC, HAMSOM (Akbar *et al.,* 2022; Rizal *et al.,* 2021; Kisnarti *et al.,* 2021). Pollution by MD has a detrimental impact on ecosystems. Enggano Island, besides having various ecosystems with high biodiversity, is also a habitat and nesting site for turtles. Various studies have proven that MD have a negative impact on ecosystems (UNEP, 2005) and turtles (Domènech *et al.*, 2019; Matiddi *et al.*, 2019), including hindering hatchlings from returning to the sea (Aguilera *et al.* 2018). In addition, fragments of plastic debris were located, presumably fragmented, but because their size was under 2.5 cm, they were neither identified nor recorded. MD can fragment after undergoing physical processes (Andrady, 2015), becoming microplastics and entering the food chain due to ingestion by various organisms (Macali *et al.,* 2018), and can have adverse effects on organisms (Prokić *et al.,* 2019; Petersen and Hubbart, 2021). Addressing the harmful consequences of marine debris pollution requires the implementation of several preventive actions. On Enggano Island, waste management is conducted independently by residents, who typically resort to burying or burning their waste. However, it can still leak to the beach, so the understanding of the importance of waste management must continue to be improved. While various government measures have been implemented to address MD pollution in the environment, these efforts have not proven effective in significantly lowering MD concentrations. Routine cleaning might be a short-term solution in reducing MD, but it is not a solution. In addition to raising public awareness, it is important for the region, together with various countries bordering the Indian Ocean, to jointly commit to the management of marine debris.

CONCLUSION

Enggano is a small, remote island in the tropical region, specifically in the Indian Ocean, where marine debris deposited on the shores poses a serious problem for the existing ecosystem. The results of the research on marine debris that washed ashore on Enggano Island from June 2021 to May 2022 showed

significant spatiotemporal variations. Each season was influenced by differences in marine debris accumulation across stations, as well as the direction and velocity of the seasonal currents. Plastic was the highest percentage found in all locations and seasons, specifically from 91.55 to 92.54%. The most common types of debris in all categories of macrodebris were Styrofoam, plastic bottles, plastic ropes and small net pieces, thin plastic wraps, and plastic cups. The prevailing assumption is that the marine debris that has accumulated on Enggano Island mainly comes from the sea. In addition to examining debris from larger neighboring islands, such as Sumatra, several bottles were analyzed for their branding, language, and provenance from other countries. These countries were China, Switzerland, Sri Lanka, India, the Maldives, Myanmar, Malaysia, Singapore, Thailand, the Philippines, Australia, Seychelles, and the Middle East, with an average percentage of Indonesian brand bottles, foreign brand bottles, and unrecognized brand bottles 58.12%, 19.59%, and 22.29%, respectively. These unidentified plastic bottles, thought to originate from abroad, are characterized by their unusual shape and color, which are not standard in Indonesian production. The survey indicated that both their prevalence and weight differ according to the season. The total marine debris collected at 10 stations over 12 months of sampling in this study was 16,382 items with a cumulative weight was 24,826 g. The average MD abundance during the study and the average weight were 0.387 ± 0.006 items/m and 211.545 ± 0.146 g/m2, respectively. The MD abundance during the JJA season ranged from 0.060-0.188 items/m2, the SON season from 0.053-0.248 items/m2, the DJF season from 0.027-0.185 items/m2, and the MAM season from 0.029–0.183 items/m2. Meanwhile, the MD weight during the JJA season ranged from 0.586-14.629 g/m2, the SON season from 1.193-7.878 g/m2, the DJF season from 0.711-3.294 g/m2, and the MAM season from 0.711-5.205 g/m2. The Kruskal-Wallis non-parametric statistical test results showed that there are substantial differences in MD abundance and weight between sampling locations. These items of marine debris are shaped by and associated with the hydrodynamic dynamics present in oceans across the globe. Consequently, additional studies are required to clarify the critical influence of ocean hydrodynamics and to identify the origins of marine debris that comes from areas outside Enggano Island. Until now, there has been no integrated waste management in Enggano. The results of this study can be the initial basis for the government to create policies to reduce stranded plastic debris for sustainable coastal area management.

AUTHOR CONTRIBUTIONS

D. Purnama performed the conception and design, conducted field sampling, analyzed and interpreted the data, and drafted the original manuscript, and manuscript edition. N.P. Zamani performed the conception and design, critical revision of the manuscript, and supervision. D.G. Bengen performed a critical revision of the manuscript and supervision. R. Saville performed the critical revision of the manuscript, and supervision. M.R. Cordova performed the conception and design, critical revision of the manuscript, and supervision.

ACKNOWLEDGMENT

The authors are grateful to Melda, Amelia, Yana, and Kiki, who served in field data collection.

CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.

org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims with regard to published maps and institutional affiliations.

ABBREVIATIONS

%	Percent
ω	The transect width
ALDFG	Abandoned, lost, and discarded fishing gear
CMS	Copernicus marine service
D	Density
DJF	The northwest monsoon in December–February
Fig.	Figure
g/m²	Gram per square meters
GNOME	General NOAA Operational Modeling Environment
GPS	Global positioning system
ha	Hectares
HAMSOM	The Hamburg Shelf Ocean Model
IO	Indian ocean
JJA	The southeast monsoon in June–August
kg	Kilograms
km	Kilometers
LMI	Low middle income
m	Meters
m²	Meter square
MAM	The first transition or inter-monsoon in March–May
MD	Marine debris
MDC	Mobidrift Client Portal
ml	Mililiters
MMT	Million metric tons
MPD	Marine plastic debris
n	Number
NAP	National Action Plan
netCDF	Network common data form
NOAA	National Oceanic and Atmospheric Administration
ODV	Ocean data view
PAST	PAleontological STatistics
PET	Polyethylene terephthalate
SEM	The south monsoon current
SJC	South Java current
SON	The second transition or inter-monsoon in September–November
UAE	United Arab Emirates

REFERENCES

Aguilera, M.; Medina-Suárez, M.; Pinós, J.; Liria-Loza, A.; Benejam, L., (2018). Marine debris as a barrier: Assessing the impacts on sea turtle hatchlings on their way to the ocean. Mar. Pollut. Bull. 137: 481-487 **(7 pages).**

Akbar, A., M.R.; Faizal, I.; Purba, N.P., (2022). The trajectory of marine debris from Cirebon city estuary, West Java, Indonesia. 15 (**9 pages**).

Ajaj, R.; Abu Jadayil, W.; Anver, H.; Aqil, E., (2022). A revision for the different reuses of polyethylene terephthalate (PET) water bottles. Sustainability. 14(8). (**14 pages**).

Alamsyah, R.; Zulkifli, A.T.A.R.; Fauzi, I., Liswahyuni, A., Permatasari, A., Wahab, H., (2022). Distribution and composition of marine debris in the shoreline area of bone bay Indonesia. Environ. Res., Eng. Manage., 78(2): 49–57 (**9 pages**).

Andrady, A. L. (2015). Persistence of Plastic Litter in the Oceans. In M. Bergmann, L. Gutow & M. Klages (Eds.), Marine Anthropogenic Litter. Cham: Springer International Publishing. (**17 pages**).

Basri, S. K.; Daud, A.; Birawida, A. B.; Maming, M.; Mukono, H. J.; Arsyad, D. S., (2024). Microplastic polymers in shellfish and fish in the coastal area. Global J. Environ. Sci. Manage., 10(4): 1477-1500. (**24 pages**).

Baulch, S.; Perry, C., (2014). Evaluating the impacts of marine debris on cetaceans Mar. Pollut. Bul., 80(1–2): 210–221 (**12 pages**).

Behera, D.P.; Kolandhasamy, P.; Sigamani, S.; Devi, L.P.; Ibrahim, Y.S., (2021). A preliminary investigation of marine litter pollution along Mandvi beach, Kachchh, Gujarat. Mar. Pollut. Bul., 165 (**6 pages**).

Blickley, L.C.; Currie, J.J.; Kaufman, G.D., (2016). Trends and drivers of debris accumulation on Maui shorelines: Implications for local mitigation strategies. Mar. Pollut. Bul., 105(1): 292–298 (**7 pages**).

Bond, T.; Ferrandiz-Mas, V.; Felipe-Sotelo, M.; van Sebille, E., (2018). The occurrence and degradation of aquatic plastic litter based on polymer physicochemical properties: A review. Critical Reviews in Environ. Sci. Technol., 48(7–9): 685–722 **(39 pages).**

Borrelle, S. B.; Ringma, J.; Lavender Law, K.; Monnahan, C.C.; Lebreton, L.; McGivern, A.; Murphy, E.; Jambeck, J.; Leonard, G.H.; Hilleary, M.A.; Eriksen, M.; Possingham, H.P.; De Frond,

H.; Gerber, L.R.; Polidoro, B.; Tahir, A.; Bernard, M.; Mallos, N.; Barnes, M.; Rochman, C.M., (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science. 369(6509): 1515–1518 (**4 pages**).

Bouwman, H.; Evans, S. W.; Cole, N.; Choong Kwet Yive, N. S.; Kylin, H., (2016). The flip-or-flop boutique: Marine debris on the shores of St Brandon's rock, an isolated tropical atoll in the Indian Ocean. Mar. Environ. Res., 114: 58–64 **(13 pages).**

BPS, (2022). Bengkulu Utara dalam Angka. BPS BU. (**399 pages**).

Brentano, R.; Petry, M.V., (2020). Marine debris ingestion and human impacts on the Pygmy sperm whale (Kogia breviceps) in southern Brazil. Mar. Pollut. Bul., 150: 110595 (**5 pages**).

Cheung, P. K.; Cheung, L.T.O.; Fok, L., (2016). Seasonal variation in the abundance of marine plastic debris in the estuary of a subtropical macro-scale drainage basin in South China. Sci. Total Environ., 562: 658–665 (**8 pages**).

Colferai, A.S.; Silva-Filho, R.P.; Martins, A.M.; Bugoni, L., (2017). Distribution pattern of anthropogenic marine debris along the gastrointestinal tract of green turtles (Chelonia mydas) as implications for rehabilitation. Mar. Pollut. Bul., 119(1): 231–237 (**7 pages**).

Cordova, M.R.; Iskandar, M.R.; Muhtadi, A.; Nurhasanah; Saville, R.; Riani, E., (2022a). Spatio-temporal variation and seasonal dynamics of stranded beach anthropogenic debris on Indonesian beach from the results of nationwide monitoring. Mar. Pollut. Bul., 182 (**15 pages**).

Cordova, M.R.; Nurhati, I.S., (2019). Major sources and monthly variations in the release of land-derived marine debris from the Greater Jakarta area, Indonesia. Sci. Rep., 9(1). (**8 pages**).

Costa,M. F.; Ivar Do Sul, J.A.; Silva-Cavalcanti, J.S.; Araújo, M.C.B.; Spengler, Â.; Tourinho, P.S., (2010). On the importance of size of plastic fragments and pellets on the strandline: A snapshot of a Brazilian beach. Environ. Monit. Assess., 168(1–4): 299–304 (**6 pages**).

Cózar A.; Echevarría F.; González-Gordillo JI; Irigoien X.; Úbeda B.; Hernández-León S.; Palma Á.T.; Navarro S.; García-de-Lomas J.; Ruiz A., (2014). Plastic debris in the open ocean. Proceeding National Academic Science. USA. 111(28): 10239–10244 (**6 pages**).

Čulin, J.; Bielić, T., (2016). Plastic Pollution from Ships. J. of Maritime and Transportation Sci., 51(1): 57–66 (**10 pages**).

Das, P., (2016). Marine Debris in Little and Great Nicobar Islands. J. Aquaculture and Mar. Bio., 4(5) **(3 Pages).**

Derraik, B., (2002). The pollution of the marine environment by plastic debris: A review. (**11 pages**).

Domènech, F.; Aznar, F. J.; Raga, J. A.; Tomás, J., 2019. Two decades of monitoring in marine debris ingestion in loggerhead sea turtle, Caretta caretta, from the western Mediterranean. Environmental Pollution 244: 367-378 **(12 Pages).**

Donohue, M.J., (2005). Eastern Pacific Ocean source of Northwestern Hawaiian Islands marine debris supported by errant fish aggregating device. Mar. Pollut. Bul., 50(8): 886–888 (**3 pages**).

Duhec, A.V.; Jeanne, R.F.; Maximenko, N.; Hafner, J., (2015). Composition and potential origin of marine debris stranded in the Western Indian Ocean on remote Alphonse Island, Seychelles. Mar. Pollut. Bul., 96: 76–86 (**11 pages**).

Duncan, E.M.; Davies, A.; Brooks, A.; Chowdhury, G.W.; Godley, B.J.; Jambeck, J.; Maddalene, T.; Napper, I.; Nelms, S.E.; Rackstraw, C.; Koldewey, H., (2020). Message in a bottle: Open source technology to track the movement of plastic pollution. PLoS ONE. 15 (**20 pages**).

Evans, S. W.; Karoo, L.; Kylin, H.; Choong, R.; Yive, K.; Cole, N.; Kylin, H.; Choong, N. S.; Neretin, L.; Tatayah, V.; Bouwman, H., (2011). Marine debris of St Brandon's Islands, Indian Ocean Marine debris of St Brandon's Islands, Indian Ocean. Conference Paper **(2 Pages).**

Geyer, R.; Jambeck, J.R.; Law, K.L., (2017). Production, use, and fate of all plastics ever made. (**6 pages**).

Gilman, E.; Humberstone, J.; Wilson, J.R.; Chassot, E.; Jackson, A.; Suuronen, P., (2022). Matching fishery-specific drivers of abandoned, lost and discarded fishing gear to relevant interventions. Mar. Policy. 141 (**29 pages**).

Gilman, E.; Musyl, M.; Suuronen, P.; Chaloupka, M.; Gorgin, S.; Wilson, J.; Kuczenski, B., (2021). Highest risk abandoned, lost and discarded fishing gear. Sci. Rep., 11(1). (**11 pages**).

Gjerdseth, E., (2017). Quantitative Analysis of Debris and Plastic Pollution on Beaches in Northern Madagascar. In Oregon Undergraduate Res. J., 10(1). (**15 pages**).

Guffogg, J.A.; Soto-Berelov, M.; Jones, S.D.; Bellman, C.J.; Lavers, J.L.; Skidmore, A.K., (2021). Towards the spectral mapping of plastic debris on beaches. Remote Sens., 13(9). (**21 pages**).

Hagen, P.E., (1990). The International Community Confronts Plastics Pollution from Ships: MARPOL Annex V and the Problem That Won't Go Away. In American University International Law Rev. 5. (**73 pages**).

Hammer, J.; Kraak, M.H.S.; Parsons, J.R., (2012). Preface. In Reviews of Environmental Contamination and Toxicology. Springer Nature. 220. (**45 pages**).

Hardesty, B.D.; Harari, J.; Isobe, A.; Lebreton, L.; Maximenko, N.; Potemra, J.; van Sebille, E.; Dick Vethaak, A.; Wilcox, C., (2017). Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. Front. Mar. Sci., 4: 1–9 (**9 pages**).

Hayati, Y.; Adrianto, L.; Krisanti, M.; Pranowo, W. S.; Kurniawan, F., (2020). Magnitudes and tourist perception of marine debris on small tourism island: Assessment of Tidung Island, Jakarta, Indonesia. Mar. Pollut. Bul., 158: 111393 (**9 pages**).

Honorato-Zimmer, D.; Kruse, K.; Knickmeier, K.; Weinmann, A.; Hinojosa, I.A.; Thiel, M., (2019). Inter-hemispherical shoreline surveys of anthropogenic marine debris – A binational citizen science project with schoolchildren. Mar. Pollut. Bul., 138: 464–473 (**10 pages**).

Ivar do Sul, J.A.; Costa, M.F., (2007). Marine debris review for Latin America and the Wider Caribbean Region: From the 1970s until now, and where do we go from here? Mar. Pollut. Bul., 54(8): 1087–1104 (**18 pages**).

Jacobsen, J.K.; Massey, L.; Gulland, F., (2010). Fatal ingestion of floating net debris by two sperm whales (Physeter macrocephalus). Mar. Pollut. Bul., 60(5), 765–767 (**3 pages**).

Jambeck, J.R.; Geyer, R.; Wilcox, C.; Siegler, T.R.; Perryman, M.; Andrady, A.; Narayan, R.; Law, K.L., (2015). Plastic waste inputs from land into the ocean. Sci., 347(6223): 768–771 (**4 pages**).

Jang, Y.C.; Lee, J.; Hong, S.; Lee, J.S.; Shim, W.J.; Song, Y.K., (2014).

Sources of plastic marine debris on beaches of Korea: More from the ocean than the land. Ocean Sci. J., 49(2): 151–162 (**12 pages**).

Jang, Y. C.; Ranatunga, R. R. M. K. P.; Mok, J. Y.; Kim, K. S.; Hong, S. Y.; Choi, Y. R.; Gunasekara, A. J. M. (2018). Composition and abundance of marine debris stranded on the beaches of Sri Lanka: Results from the first island-wide survey. Mar. Pollut. Bul., 128: 126–131 (**6 pages**).

Jayasiri, H.B.; Purushothaman, C.S.; Vennila, A., (2013). Quantitative analysis of plastic debris on recreational beaches in Mumbai, India. Mar. Pollut. Bul., 77(1–2): 107–112 (**6 pages**).

Johan, Y.; Renta, P.P.; Muqsit, A.; Purnama, D.; Maryani, L.; Hiriman, P.; Rizky, F.; Astuti, A.F.; Yunisti, T., 2020. Analisis Sampah Laut (Marine Debris) Di Pantai Kualo Kota Bengkulu. J. Enggano. 5(2): 273–289 (**17 pages**).

Kisnarti, E. A.; Ningsih, N.S.; Putri, M.R.; Hendiarti, N.; Tuah, U.H.; Putih, J.P., (2021). The movement of plastic marine debris in indonesian seas using a trajectory model. J. Segara. 17(3): 145–154 (**10 pages**).

Krishnakumara, S.; Anbalagana, S.; Kasilingamb, K.; Smrithic, P.; Anbazhagic, S.; Srinivasalua, S., (2020). Assessment of plastic debris in remote islands of the Andaman and Nicobar Archipelago, India. Mar. Pollut. Bul., 151 (**12 pages**).

Krishnakumar, S.; Srinivasalu, S.; Saravanan, P.; Vidyasakar, A.; Magesh, N.S., (2018). A preliminary study on coastal debris in Nallathanni Island, Gulf of Mannar Biosphere Reserve, Southeast coast of India. Mar. Pollut. Bul., 131: 547–551 (**5 pages**).

Kumar, R.; Verma, A.; Shome, A.; Sinha, R.; Sinha, S.; Jha, P.K.; Kumar, R., Kumar, P.; Shubham; Das, S.; Sharma, P.; Prasad, P.V.V., (2021). Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. In Sustainability. 13(17): MDPI. (**41 pages**).

Kuo, F.J.; Huang, H.W., (2014). Strategy for mitigation of marine debris: Analysis of sources and composition of marine debris in northern Taiwan. Mar. Pollut. Bul., 83(1): 70–78 (**9 pages**).

Lavers, J.L.; Dicks, L.; Dicks, M.R.; Finger, A., (2019). Significant plastic accumulation on the Cocos (Keeling) Islands, Australia. Sci. Rep., 9(1). (**9 pages**).

Lebreton, L.; Egger, M.; Slat, B., (2019). A global mass budget for positively buoyant macroplastic debris in the ocean. Sci. Rep., 9(1). (**8 pages**).

Lippiatt, S.; Opfer, S.; Arthur, C., (2013). Marine Debris Monitoring and Assessment: Recommendations for Monitoring Debris Trends in the Marine Environment. NOAA Technical Memorandum, NOS-OR and R-46: 88. (**88 pages**).

Lo, H.S.; Lee, Y.K.; Po, B.H. K.; Wong, L.C.; Xu, X.; Wong, C.F.; Wong, C.Y.; Tam, N.F.Y.; Cheung, S.G., (2020). Impacts of Typhoon Mangkhut in 2018 on the deposition of marine debris and microplastics on beaches in Hong Kong. Sci. Total Environ., 716: 137172. (**9 pages**).

Macali, A.; Semenov, A.; Venuti, V.; Crupi, V.; D'Amico, F.; Rossi, B.; Corsi, I.; Bergami, E., (2018). Episodic records of jellyfish ingestion of plastic items reveal a novel pathway for trophic transference of marine litter. Sci. Rep., 8(1). (**5 pages**)

Martin J.M., (2013). Marine debris removal: One year of effort by the Georgia Sea Turtle-Center-Marine Debris Initiative. Mar Pollut Bull., 74(1): 165–169. (**5 pages**).

Matiddi, M.; DeLucia, G. A.; Silvestri, C.; Darmon, G.; Tomás, J.; Pham, C. K.; Camedda, A.; Vandeperre, F.; Claro, F.; Kaska, Y.; Kaberi, H.; Revuelta, O.; Piermarini, R.; Daffina, R.; Pisapia, M.; Genta, D.; Sözbilen, D.; Bradai, M. N.; Rodríguez, Y.; Gambaiani, D.; Tsangaris, C.; Chaieb, O.; Moussier, J.; Loza, A. L.; Miaud, C., (2019). Data collection on marine litter ingestion in sea turtles and thresholds for good environmental status. J. Visualized Exper. 2019: 1-9 **(9 pages).**

Mauludy, M.S.; Yunanto, A.; Yona, D., (2019). Microplastic Abundances in the Sediment of Coastal Beaches in Badung, Bali. J. Perikanan Universitas Gadjah Mada. 21(2): 73 (**6 pages**).

Metadata Peraturan, (2018). Perpres Nomor 83 Tahun 2018 tentang Penanganan Sampah Laut., 83 (**10 pages**).

Morishige, C.; Donohue, M.J.; Flint, E.; Swenson, C.; Woolaway, C., (2007). Factors affecting marine debris deposition at French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument, 1990-2006. Mar. Pollut. Bul., 54(8): 1162–1169 (**8 pages**).

Mrosovsky, N.; Ryan, G.D.; James, M.C., (2009). Leatherback turtles: The menace of plastic. Mar. Pollut. Bul., 58(2): 287–289 (**3 pages**).

Mugilarasan, M.; Karthik, R.; Purvaja, R.; Robin, R. S.; Subbareddy, B.; Hariharan, G.; Rohan, S.; Jinoj, T.P.S.; Anandavelu, I.; Pugalenthi, P.; Ramesh, R., (2021). Spatiotemporal variations in anthropogenic marine litter pollution along the northeast beaches of India. Environ. Pollut., 280 (**14 pages**).

Nakajima, R.; Tsuchiya, M.; Yabuki, A.; Masuda, S.; Kitahashi, T.; Nagano, Y.; Ikuta, T.; Isobe, N.; Nakata, H.; Ritchie, H.; Oguri, K.; Osafune, S.; Kawamura, K.; Suzukawa, M.; Yamauchi, T.; Iijima, K.; Yoshida, T.; Chiba, S.; Fujikura, K., (2021). Massive occurrence of benthic plastic debris at the abyssal seafloor beneath the Kuroshio Extension, the North West Pacific. Mar. Pollut. Bul., 166 (**9 pages**).

Nurhasanah; Hasrianti; Hakim, L.; Riani, E.; Iswari, M. Y.; Cordova, M. R., (2024). Microplastic contamination in the gut and gills of commercial marine fish. Global J. Environ. Sci. and Manage., 10(4), 1897–1916 (**20 pages**).

Ondara, K.; Dhiauddin, R.; Putih, J.P., (2021). Identification of floating marine debris in the Banda Aceh estuary. Agustus. 17(2): 75–82 (**8 pages**).

Ourmieres, Y.; Mansui, J.; Molcard, A.; Galgani, F.; Poitou, I., (2018). The boundary current role on the transport and stranding of floating marine litter: The French Riviera case. Continental Shelf Res., 155, 11–20 (**10 pages**).

Pattiaratchi, C.; Van Der Mheen, M.; Schlundt, C.; Narayanaswamy, B.E.; Sura, A.; Hajbane, S.; White, R.; Kumar, N.; Fernandes, M.; Wijeratne, S., (2022). Plastics in the Indian Ocean-sources, transport, distribution, and impacts. In Ocean Sci., 18 (1): 1–28 (2**8 pages**).

Pauly, D.; Zeller, D., (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nat. Commun., 7 (**9 pages**).

Peng, X.; Chen, M.; Chen, S.; Dasgupta, S.; Xu, H.; Ta, K.; Du, M.; Li, J.; Guo, Z.; Bai, S., (2018). Microplastics contaminate the deepest part of the world's ocean. Geochemical Perspectives Lett., 9: 1–5 (**5 pages**).

Patterson Edward, J.K.; Mathews, G.; Raj, K.D.; Laju, R.L.; Bharath, M.S.; Kumar, P.D.; Arasamuthu, A.; Grimsditch, G., (2020). Marine debris — An emerging threat to the reef areas of Gulf of Mannar, India. Mar. Pollut. Bul., 151 (**8 pages**).

Petersen, F.; Hubbart, J.A., (2021). The occurrence and transport of microplastics: The state of the science. Sci. Tot. Environ. 758: 143936 **(12 pages).**

Petry, L.; Bugoni, L.; Krauseand, M.V., (2001). Marine debris and human impacts on sea turtles in southern Brazil. Mar. Pollut. Bul., 42(12): 1330–1334 (**5 pages**).

Prokić, M. D.; Radovanović, T.B.; Gavrić, J.P.; Faggio, C., (2019). Ecotoxicological effects of microplastics: Examination of biomarkers, current state and future perspectives. TrAC - Trends in Analytical Chem., 111: 37–46 (**10 pages**).

Purba, N.P.; Faizal, I.; Cordova, M.R.; Abimanyu, A.; Afandi, N.K.A.; Indriawan, D.; Khan, A.M.A., (2021). Marine Debris Pathway Across Indonesian Boundary Seas. J. Eco. Eng., 22(3): 82–98. (**17 pages**).

Rahmania, R.; Setiawan, A.; Tussadiah, A.; Kusumaningrum, P. D.; Yulius; Prihantono, J.; Gautama, B. G.; Pranowo, W.S.; Aisyah, Nugraha, A.W.; Gusmawati, N.F.; Widjanarko, E.; Arifin, T., (2021). Mapping seasonal marine debris patterns and potential hotspots in Banten Bay, Indonesia. IOP Conference Series: Earth Environ. Sci., 763(1) (**12 pages**).

Reisser, J.; Slat, B.; Noble, K.; Du Plessis, K.; Epp, M.; Proietti, M.; De Sonneville, J.; Becker, T.; Pattiaratchi, C., (2015). The vertical distribution of buoyant plastics at sea: An observational study in the North Atlantic Gyre. Biogeosciences. 12(4): 1249–1256 (**8 pages**).

Richardson, K.; Wilcox, C.; Vince, J.; Hardesty, B.D., (2021). Challenges and misperceptions around global fishing gear loss estimates. Mar. Policy. 129. (**5 pages**).

Rizal, A.; Gautama, B.G.; Pranowo, W.S.; Farhan, A.R.; Siong, K.; Harjono, M.R.; Voisin, J.B.; Maes, C.; Dobler, D.; Berlianty, D.; Priyono, B.; Dufau, C.; Lucas, M.; Fauny, O.; Rahmania, R., (2021). Tracking the Stranded Area of Marine Debris in Indonesian coasts by using Floating Drifter. IOP Conference Series: Earth Environ. Sci., 925(1). (**11 pages**).

Rothäusler, E.; Jormalainen, V.; Gutow, L.; Thiel, M., (2019). Low abundance of floating marine debris in the northern Baltic Sea. Mar. Pollut. Bul., 149 (**5 pages**).

Ryan, P.G.; Perold, V., (2021). Limited dispersal of riverine litter onto nearby beaches during rainfall events. Estuarine Coastal Shelf Sci., 251 (**9 pages**).

Sari, D.I.; Aditya B.A.; Ramadhan R.I., (2015). Distribusi mikroplastik pada sedimen di Muara Badak, Kabupaten Kutai Kartanegara. Depik. 4(3): 121–131 (**11 pages**).

Savage, J.; Chamberlain, A.; Fellows, M.; Jones, R.; Letessier, T. B.; Llewellyn, F.; Morritt, D.; Rowcliffe, M.; Koldewey, H., (2024). Big brands impact small islands: Sources of plastic pollution in a remote and protected archipelago. Mar. Pollut. Bul., 203 **(11 pages).**

Sinopoli, M.; Cillari, T.; Andaloro, F.; Berti, C.; Consoli, P.; Galgani, F.; Romeo, T., (2020). Are FADs a significant source of marine litter? Assessment of released debris and mitigation strategy in the Mediterranean Sea. J. Environ. Manage., 253: 109749 (**8 pages**).

Sprintall, J.; Wijffels, S.E.; Molcard, R.; Jaya, I., (2009). Direct estimates of the indonesian throughflow entering the indian ocean: 2004-2006. J. Geophysical Res., Oceans. 114(7). (**20 pages**).

Sridhar, K.R.; Bhat, R., (2009). Plastic litter along the beaches of Karnataka, southwest coast of India. Asian J. Water Environ. Pollut., 6(2): 87-93 **(7 pages).**

Suteja, Y.; Atmadipoera, A.S.; Riani, E.; Nurjaya, I.W.; Nugroho, D.; Cordova, M.R., (2021). Spatial and temporal distribution of microplastic in surface water of tropical estuary: Case study in Benoa Bay, Bali, Indonesia. Mar. Pollut. Bul., 163(1): 111979 (**14 pages**).

Suyadi; Nugroho, D. A.; Irawan, A.; Pelasula, D.; Ruli, F.; Islami, M. M.; Alik, R.; Tala, D. J.; Pay, L.; Matuankotta, C., Leatemia, A. S.; Naroli, I., (2021). Biodiversity in the coastal ecosystems of small islands and its conservation status. IOP Conference Series: Earth Environ. Sci., 762(1) **(15 pages).**

Takarina, N. D.; Purwiyanto, A. I. S.; Rasud, A. A.; Arifin, A. A.; Suteja, Y., (2022). Microplastic abundance and distribution in surface water and sediment collected from the coastal area. Global J. Environ. Sci. Manage., 8(2): 183–196 (**14 pages**).

Thiel, M.; Lorca, B. B.; Bravo, L.; Hinojosa, I. A.; Meneses, H.Z., (2021). Daily accumulation rates of marine litter on the shores of Rapa Nui (Easter Island) in the South Pacific Ocean. Mar. Pollut. Bul., 169 (**8 pages**).

Triana, K.; Wahyudi, A.J.; Murakami-Sugihara, N.; Ogawa, H., (2021). Spatial and temporal variations in particulate organic carbon in Indonesian waters over two decades. Mar. Freshwater Res., 72(12): 1782–1797. (**31 pages).**

UNEP, (2005). Marine Litter An analytical. United Nations Environment Programme. 47. (**58 pages**).

Unger, A.; Harrison, N., (2016). Fisheries as a source of marine debris on beaches in the United Kingdom. Mar. Pollut. Bul., 107(1): 52–58 (**7 pages**).

Van Der Mheen, M.; Van Sebille, E.; Pattiaratchi, C., (2020). Beaching patterns of plastic debris along the Indian Ocean rim. Ocean Sci., 16(5): 1317–1336 (**20 pages**).

Vélez-Rubio, G.M.; Teryda, N.; Asaroff, P.E.; Estrades, A.; Rodriguez, D.; Tomás, J., (2018). Differential impact of marine debris ingestion during ontogenetic dietary shift of green turtles in Uruguayan waters. Mar. Pollut. Bul., 127: 603–611. (**9 pages**).

Vogt-Vincent, N. S.; Burt, A. J.; Kaplan, D. M.; Mitarai, S.; Turnbull, L. A.; Johnson, H. L., (2023). Sources of marine debris for Seychelles and other remote islands in the western Indian Ocean. Mar. Pollut. Bul., 187 **(18 pages).**

Wilcox, C.; Puckridge, M.; Schuyler, Q.A.; Townsend, K.; Hardesty, B. D., (2018). A quantitative analysis linking sea turtle mortality and plastic debris ingestion. Sci. Rep., 8(1): 1–11 (**11 pages**).

Woods, J.S.; Rødder, G.; Verones, F., (2019). An effect factor approach for quantifying the entanglement impact on marine species of macroplastic debris within life cycle impact assessment. Eco. Indicators, 99: 61–66 (**6 pages**).

Zhang, W.; Zhang, S.; Wang, J.; Wang, Y.; Mu, J.; Wang, P.; Lin, X.; Ma, D., (2017). Microplastic pollution in the surface waters of the Bohai Sea, China. Environ. Pollut., 231: 541–548 (**20 pages**).

Zhou, P.; Huang, C.; Fang, H., Cai, W.; Li, D.; Li, X.; Yu, H., (2011). The abundance, composition and sources of marine debris in coastal seawaters or beaches around the northern South China Sea (China). Mar. Pollut. Bul., 62(9): 1998–2007 (**10 pages**).

AUTHOR (S) BIOSKETCHES

Purnama, D., Ph.D. Candidate., Assistant Professor, Marine Science Department, Bengkulu University, Jl. WR. Supratman Kandang Limun, Bengkulu 38371 Indonesia.
▪ Email: *dewipurnama@unib.ac.id*
▪ ORCID: 0009-0008-9513-8411
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57196435658
▪ Homepage: https://agriculture.unib.ac.id/bms/?u_member=dewi-purnama-s-pi-m-si

Zamani, N.P., Ph.D., Professor, Department of Marine Sciences and Technology, Faculty of Fisheries and Marine Science, IPB University, Bogor 16680, Indonesia.
▪ Email: *neviaty@apps.ipb.ac.id*
▪ ORCID: 0000-0002-3312-2333
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 55991633900
▪ Homepage: https://itk.ipb.ac.id/dr-ir-neviaty-p-zamani-m-sc/

Bengen, D.G., Ph.D., Professor, Department of Marine Sciences and Technology, Faculty of Fisheries and Marine Science, IPB University, Bogor 16680, Indonesia.
▪ Email: *dieter@indo.net.id*
▪ ORCID: 0000-0002-3880-5117
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 55845650900
▪ Homepage: http://itk.ipb.ac.id/~itkipb/prof-dr-ir-dietriech-g-bengen-dea/

Saville, R., Ph.D., Associate Professor, Faculty of International Agriculture and Food Studies, Tokyo University of Agriculture, Setagaya Campus 1-1-1 Sakuragaoka, Setagaya-ku, Tokyo 156-8502, Japan.
▪ Email: *sr203424@nodai.ac.jp*
▪ ORCID: 0000-0003-0271-9249
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 55902315000
▪ Homepage: http://dbs.nodai.ac.jp/html/100001221_en.html

Cordova, M.R., Ph.D. Professor, Research Center for Oceanography, National Research and Innovation Agency Republic of Indonesia, Jakarta, Indonesia.
▪ Email: *muha125@brin.go.id*
▪ ORCID: 0000-0002-4756-9646
▪ Web of Science ResearcherID: AAL-7273-2020
▪ Scopus Author ID: 56147418700
▪ Homepage: https://siin.brin.go.id/smi/7F0D69E8-2A0B-4C8E-8E51-69D3734456E0

HOW TO CITE THIS ARTICLE

Purnama, D.; Zamani, N.P.; Bengen D.G.; Saville, R.; Cordova, M.R., (2025). Spatial heterogeneity of marine debris distribution on a tropical remote island shoreline. Global J. Environ. Sci. Manage., 11(2): 461-480.

DOI: 10.22034/gjesm.2025.02.06

URL: https://www.gjesm.net/article_719312.html

Global J. Environ. Sci. Manage. 11(2): 481-496, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Optimizing industrial and domestic water consumption efficiency for sustainable growth through data envelopment analysis

Z. Bayat, J. Vives Costa*, J.J. de Felipe Blanch

Department of Mining, Industrial and ICT Engineering, E.P.S.E. Manresa, Universitat Politécnica de Catalunya, Barcelona, Spain

ARTICLE INFO

Article History:
Received 17 September 2024
Revised 21 December 2024
Accepted 24 January 2025

Keywords:
Constant return to scale
Data envelopment analysis (DEA)
Efficiency evaluation
Variable return to scale
Water management

ABSTRACT

BACKGROUND AND OBJECTIVES: Water resources are essential for socio-economic development and quality of life, but limited availability, especially in regions with uneven distribution, poses challenges. The rapid economic development in Catalonia has led to considerable stress related to water scarcity, emphasizing the urgent requirement for improved resource management practices. The objectives of the current study were to evaluate the existing water resource consumption efficiency in key sectors across Catalonia and suggest workable strategies for water management to ensure sustainability.

METHODS: The water resource consumption efficiency of 42 Catalan regions in 2021 was analyzed using 50 data envelopment analysis models, employing both constant and variable returns to scale. Information regarding gross domestic product and water usage was sourced from regional governmental sources. The analysis utilized both input and output-oriented models to pinpoint areas where efficiency could be enhanced.

FINDINGS: The findings indicated that the industrial sector in Barcelona reached peak efficiency in water resource utilization, earning a score of 1 in both models, which sets a new benchmark. Ribera d'Ebre reached full efficiency in domestic water consumption with a score of 1. Conversely, regions such as Priorat, Terra Alta, and Barcelona showed inefficiencies, suggesting that to achieve full efficiency, Priorat, Terra Alta, and Barcelona could reduce inputs by approximately 63 percent, 44 percent, and 26 percent, respectively, or increase outputs by approximately 172 percent, 78 percent, and 36 percent respectively, holding other factors constant.

CONCLUSION: Focusing on efficiency enhancements in areas that currently score lower can greatly aid in achieving sustainable water management practices in Catalonia. Embracing proven methods from exemplary regions has the potential to strengthen water resource management, contributing to both economic resilience and environmental sustainability.

DOI: 10.22034/gjesm.2025.02.07

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
43

NUMBER OF FIGURES
10

NUMBER OF TABLES
2

*Corresponding Author:
Email: *jordi.vives@upc.edu*
Phone: +3461 889 0950
ORCID: 0000-0003-3854-775X

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

As a special natural resource, water is a necessity for socioeconomic development as well as human life. The uneven water resources (WRs) distribution further decreases limited availability. According to the World Economic Forum (2014), the freshwater crisis has escalated in severity, driven by the impacts of climate change and the rapid increase in population. The lack of WRs has turned into a significant global challenge, particularly noticeable in areas characterized by arid and semiarid climates (Soltanjalili *et al.,* 2013; Han *et al.,* 2013; Medrano *et al.,* 2015). WRs, which are a fundamental part of social, economic, and environmental systems, face various challenges, including the complexities of hydrological cycles, socioeconomic factors, and diverse stakeholder perspectives regarding water use (Tidwell *et al.,* 2004; Langsdale *et al.,* 2007; Susnik *et al.,* 2013). Climate change is a crucial factor in the sustainable management of WRs (Qin *et al.,* 2019). Considering the diverse influences of factors like climate change, regular monitoring is vital for modifying strategies and guaranteeing enduring efficiency and sustainability. Also, as a result of population growth, agricultural expansion, and industrial development, the rising demand for water leads to excessive extraction from groundwater sources. This substantial degree of extraction disturbs the balance among the different elements of these resources (Mohtashami *et al.,* 2024). Moreover, the rapid pace of economic growth and urbanization in recent years has led to significant WR consumption and substantial wastewater discharge. Given these conditions, water has turned into a significant limiting factor for both socio-economic growth and urban development (Tomohiro *et al.,* 2006; Rousta *et al.,* 2023). Water is essential to economic development; threats to water security are estimated to be United States Dollars ($US) 500 billion annually, or around 1 percent (%) of the world's gross domestic product (GDP) (Hu and Tan, 2018). An essential challenge lies in aligning socioeconomic development with the responsible use of WR in the context of their limited availability. Enhancing water resource consumption efficiency (WRCE) is broadly recognized as a key method for addressing these issues (Ren *et al.,* 2017). WRCE is a necessary topic for research, especially as the metrics of water scarcity become increasingly serious. It is crucial to discover methods that will boost this efficiency in order to tackle issues related to the environment and resource challenges (Hsieh *et al.,* 2019). WRCE represents a wide-ranging concept that can be described in multiple ways, such as through the lens of engineering or the perspective of production (Cai *et al.,* 2011). Efficiency pertains to the overall relationship between all outputs and inputs within a production process (Rodríguez Díaz *et al.,* 2004). Two major approaches to measuring efficiency have evolved: parametric and non-parametric methods, with the stochastic frontier analysis (SFA) and data envelopment analysis (DEA) being the most common techniques. Compared to econometric techniques, DEA presents considerable advantages, particularly due to its lack of assumptions concerning the functional form of frontier technology and the distribution of inefficiency, in contrast to SFA, which relies on the assumption of normally distributed errors.. Also, mixed models are more complex and require higher technical knowledge, while DEA is a simpler and more understandable method. Additionally, DEA constructs a surface over the data, allowing for comparisons of different production techniques using a performance index. DEA is based on the idea that a production unit that uses less input than another to produce the same output is more efficient. A production frontier is established while simultaneously deriving efficiency measures (Speelman *et al.,* 2008). DEA, a non-parametric approach, operates through linear programming techniques, and was initially introduced by Charnes *et al.* (1978). In the context of DEA, the fundamental unit of assessment is termed the decision-making unit (DMU). Each DMU is organized into a collective referred to as an evaluation group. To determine the efficiency of each DMU, comparison is made to other DMUs in this group, a process known as benchmarking, as indicated in prior studies such as those of Frija *et al.* (2009) and Susaeta *et al.* (2016). A series of linear programming analyses within the evaluation group establishes the optimal performance frontier, which acts as a benchmark for assessing all DMUs. This approach avoids relying on a functional form, making this a robust way to represent the relationship of DMUs, using a non-parametric production frontier (Frija *et al.,* 2011; Ali and Klein, 2014; Bonfiglio *et al.,* 2017). When a DMU achieves a technical value of one, this indicates that the operation aligns with the most efficient production boundary. This signifies

that the existing production level corresponds to the highest potential, reflecting optimized efficiency in water usage. However, an efficiency score lower than one denotes that a particular DMU has not yet achieved full optimization, implying that gains in efficiency may be achievable. Consequently, DEA assesses the disparity between an individual DMU and the optimal operational methods observed in the analyzed dataset (Manjunatha *et al*., 2011). The DEA approach can manage single or multiple inputs and outputs, identifies the most efficient DMU, and is effective for evaluating WRCE and environmental efficiency (Mardani *et al.,* 2018). Speelman *et al.* (2008) used DEA techniques to assess WRCE in small-scale irrigation schemes in South Africa's Northwest Province, revealing significant technical inefficiencies among farmers and offering insights for policy and extension services to improve efficiency. Bian *et al.* (2014) examined the water crisis in China in the context of its economic development, suggesting a DEA method to evaluate urban water systems. Their findings indicated that enhancing system efficiency and utilizing more treated wastewater could lead to substantial water savings, even in light of existing data constraints. Ren *et al.* (2017) presented an extended DEA method to analyze WRCE and related issues, incorporating regional WR metabolic theory. Applied to Gansu Province, China, the method has enabled decision-makers to assess comprehensive WRCE, identify negative factors, and provide recommendations for efficient WR management in different cities. Wang *et al.* (2018) analyzed WRCE, using DEA, and found room for improvement, with economically developed Eastern provinces showing the highest efficiency. Elements such as reliance on exports and advancements in technology have contributed positively to efficiency, whereas the effects of industrial structure and government intervention have been relatively minimal. These findings have informed government planning for WR development and regional sustainability. Geng *et al.* (2019) used DEA to evaluate agricultural WRCE and results have revealed significant improvement post-2008, especially in blue WRCE. In terms of pure technical efficiency (PTE), Northern China exhibits superior performance, while Southern China is more proficient in total technical efficiency (TE) in particular situations. A study by Hsieh *et al.* (2019) used resampling DEA to evaluate WRCE, incorporating inputs like water supply and GDP and outputs like wastewater management and pollutant levels. The findings indicate notable regional discrepancies, with effective provinces like Tibet and Guangdong illustrating the importance of developing specific water policies and implementing stricter monitoring of pollutants to mitigate inequalities. In addition, other research has been conducted all over the world, which are briefly mentioned: Ali and Klein (2014) used DEA to evaluate irrigation efficiency in southern Alberta (2009–2012). Azad *et al.* (2015) applied non-radial DEA to Australian irrigated farms, finding lower efficiency in water management despite strong overall performance. Gungor-Demirci *et al.* (2018) used DEA to investigate California water utility districts during 2014, highlighting DEA's utility in identifying performance gaps and guiding improvements. While global concerns over water scarcity are well-documented, Catalonia's unique context demands focused investigation. Given the ongoing economic expansion, it is vital to comprehend the implications for water demand and consumption patterns to formulate sustainable water management strategies in the area. According to the annual report on the economy of the region of Catalonia by the Ministry of Economy and Finance, the year 2021 was characterized by a significant progressive improvement in economic activity on a worldwide scale. This year, Catalonia's GDP experienced a growth of 5.8%, outpacing the growth rates of the eurozone at 5.4% and Spain at 5.1%. In 2021, all major economic sectors experienced growth, with the services sector expanding significantly by 6.3% and the manufacturing industry increasing by 5.3%. In the second half of the year, the services sector showed remarkable vitality, especially in industries that require direct physical interaction, such as hospitality and leisure activities. When comparing the changes in Catalonia's GDP by sector to that of the euro area, the commerce, transportation, and hospitality sectors made a notable positive contribution of 2.7 percentage points, despite being the most impacted by the health crisis in 2020. With the onset of 2022, the services sector stood out as the most vibrant, while agriculture, manufacturing, industry, and construction struggled with heightened challenges related to supply chain issues, rising energy costs, and other input expenses (Government of Catalonia, 2022). This shows the economy's vulnerability due to various conditions,

including climate changes and the amount of available water. In addition, in this report is stated that higher economic growth in the region is predicted for the coming years and that this economic growth requires more use of WRs. Global apprehensions regarding water scarcity, particularly in arid areas, are prevalent; however, the specific circumstances in Catalonia necessitate a detailed examination. In light of the current economic growth, it is essential to evaluate the impacts on water demand and consumption trends in order to develop effective and sustainable water management strategies for the region. The next sections elaborate on methodology, data collection, results, discussion, and conclusion. The current study aims to assess WRCE, emphasizing correlation with GDP growth. This study was conducted in Catalonia, Spain, in 2023.

MATERIALS AND METHODS

DEA approach

This study utilizes DEA to assess the TE of DMUs within the Catalunya region, with a specific emphasis on evaluating industrial water consumption (IWC) and domestic water consumption (DWC). The DEA framework is an effective and frequently utilized approach for assessing efficiency, noted for its simplicity, absence of stringent statistical assumptions, and proficiency in accommodating multiple inputs and outputs. Furthermore, DEA allows us to directly compare the performance of different regions and objectively show which regions are performing better in resource utilization. The methodology is based on the groundwork developed by Farrell (1957), which was subsequently expanded upon in the Charnes, Cooper, and Rhodes (CCR) model and the Banker, Charnes, and Cooper (BCC) model (Speelman *et al.,* 2008; Frija *et al.,* 2009; Chen *et al.,* 2015). The CCR model functions under the principle of constant returns to scale (CRS), meaning that modifications in input quantities will produce directly proportional variations in output quantities. However, increased inputs do not necessarily result in proportional increases in output (Speelman *et al.,* 2008). The BCC model, in contrast, uses an assumption of variable returns to scale (VRS). While the CCR model assumes proportional increases in outputs as inputs increase, the BCC model (Banker *et al.,* 1984) takes into account the possibility of a non-proportional input-output relationship, which is particularly pertinent in an agricultural context that is dealing with the management of water. Utilizing a VRS rather than a constant return allows the BCC model to distinguish between PTE and from Scale Efficiency (SE). This differentiation allows the measurement of whether DMUs are operating at ideal production scale (Ren *et al.,* 2017). Consequently, adopting a VRS methodology might be more fitting for the assessment of technical efficiencies in scenarios involving irrigated farming (Rodríguez Díaz *et al.,* 2004). DEA remains a well-known and frequently used method for assessing efficiency. The analytical objectives determine the focus of the DEA models: the input orientation model aims to enhance efficiency by minimizing inputs while maintaining consistent outputs, whereas the output orientation model seeks to maximize outputs while keeping input levels constant (Geng *et al.,* 2019). Regions facing constraints in WRs can adjust their economic activities by employing strategies that optimize outputs without altering input levels, as demonstrated by the output orientation model. To provide a clear mathematical explanation, consider n DMUs, where each DMU j (for j = 1, 2, 3, ..., n) utilizes m inputs to produce s outputs. Let x_{ij} denote the i-th input of DMU j, and y_{rj} represent the r-th output of DMUj. The input and output vectors for DMUj can be defined as $x_j = (x_{1j}, x_{2j}, x_{3j}, \ldots, x_{mj})^T$ and $y_j = (y_{1j}, y_{2j}, y_{3j}, \ldots, y_{mj})^T$, respectively. The term θ, with a value between zero and one, indicates TE. Moreover, θ also functions as a weighting factor. The input and output vectors correspond with a particular DMU referred to as DMU_{j0}. DEA models, using equation (Eq.) 1 (Geng *et al.,* 2019; Charnes *et al.,* 1978; Coelli *et al.,* 2005):

$$\begin{aligned} &\text{Min } \theta \\ &\text{s.t. } \Sigma_{j=1}^{n}\lambda_j x_j \leq \theta x_0 \\ &\Sigma_{j=1}^{n}\lambda_j x_j \geq y_0 \\ &\Sigma_{j=1}^{n}\lambda_j = 1 \\ &\lambda_j \geq 0 \end{aligned} \quad (1)$$

By introducing a slack variable, denoted by S^-, and a surplus variable, denoted by S^+, the initial inequality restrictions found which are transformed into equality conditions, using Eq. 2 (Geng *et al.,* 2019; Charnes *et al.,* 1978; Coelli *et al.,* 2005):

$$\begin{aligned} &\text{Min } \theta \\ &\text{s.t. } \Sigma_{j=1}^{n;} \lambda_j x_j + S^- = \\ &\Sigma_{j=1}^{n} \lambda_j y_j - S^+ = y_0 \\ &\lambda_J \geq 0,\ \Sigma_{j=1}^{n} \lambda_j = 1 \\ &S^- \geq 0, S^+ \geq 0 \end{aligned} \quad (2)$$

The SE can be determined by calculating the TE and PTE scores measured on a scale from 0 to 1 and reflects how scale size impacts the productivity of a DMU. A value of 1 signifies that the DMU is operating at the most efficient scale, while a value below 1 indicates inefficiency, using Eq. 3 (Geng *et al.*, 2019; Gadanakis *et al.*, 2015; Coelli *et al.*, 2002, Coelli 1996).

$$SE=TE/PTE \quad (3)$$

This analysis utilized the Benchmarking library in R Studio software for all computations.

Data sources and indicator selection

The economic factor was evaluated by examining the GDP for the Catalonia region in 2021, with data sourced from the official statistical agency Idescat (2023), specifically accessing data for the Catalunya region for the year 2021. Data on water consumption, encompassing domestic and industrial use, has been obtained from the Agencia Catalana de l'Aigua (2022) for the Catalunya region in 2021 (Table 1). Initially, efficiency was analyzed using IWC as input , and the analysis was repeated with DWC as input. Ultimately, a detailed assessment was performed by simultaneously integrating both IWC and DWC as input variables. This approach allowed for the evaluation of the stability of efficiency scores and ensured that results are not overly dependent on the selection of specific input variables, thereby enhancing the robustness of the conclusions.

A thorough analysis was conducted by referencing the Summary of the 2021 Annual Report on the Catalan Economy, which was released in June 2022 by the Government of Catalonia, Ministry of the Economy and Finance (Government of Catalonia, 2022). The DMUs for this analysis include the following regions within Catalunya listed in Table 2. Noting that the regions of Ribera d'Ebre (Rib) and Baix Ebre (BaiEbr) receive water supply from the Ebro River basin, which originates from areas outside Catalonia, is important. Conversely, the other regions derive their water from internal basins formed by numerous small rivers that originate in the Pyrenees within Catalonia. This distinction in water sources is crucial for understanding the regional differences in WRCE. By utilizing these data sources and selecting appropriate indicators, The efficiency and productivity of each region within Catalunya in terms of both GDP generation and water consumption in the year 2021 are aimed to be evaluated.

RESULTS AND DISCUSSION

Industrial water consumption

In the realm of input orientation efficiency, Barc stands out as a paragon of operational excellence. Based on the data provided, Barc reaches its highest efficiency levels under both CRS and VRS conditions. At an optimal scale, the IWC in Barc showcases exceptional efficiency, with both input and output slack variables measuring zero. A study by Pascual-Pañach *et al.* (2024) shows that the temporal case-based reasoning approach, utilizing artificial intelligence techniques, has been implemented in a real facility for local water management in Barc. This strategy markedly increases the accuracy of solutions and case evaluations relative to traditional approaches, suggesting that Barc adeptly employs advanced technologies to refine WR management, thus substantiating its outstanding analytical performance. This indicates that Barc effectively utilizes all inputs to achieve the desired level of outputs without any excess, positioning Barc as a benchmark for other DMUs. This aligns with the views presented in research conducted by Speelman *et al.* (2008) and Bian *et al.* (2014). By replicating

Table 1: Descriptive of the input and output parameters used in the DEA model

Variables	Parameter types	Units
Industrial water consumption	Input	m^3
Domestic water consumption	Input	m^3
Industrial and domestic water consumption	Input	m^3
Gross domestic product	Output	In millions of $US

Table 2: Data on water consumption, GDP, and DMUs

Regions	Domestic m^3	Industrial m^3	GDP (in millions of $US)	Regions	Domestic m^3	Industrial m^3	GDP (in millions of $US)
Alt camp (AltC)	1714466	2915294	1799.2	Moianès (Moi)	675920	669991	360.7
Alt empordà (AltEm)	8595769	4172993	4167.0	Montsià (Mon)	2836697	1935397	1677.5
Alt penedès (AltP)	4603268	3011623	3803.3	Noguera (Nog)	1786724	1705103	1154.7
Alt urgell (AltU)	1053239	1416721	557.5	Osona (Oso)	6657825	8233359	5938.6
Alta ribagorça (AltR)	461015	201657	112.8	Pallars Jussà (PalJ)	807845	257622	374.0
Anoia (Ano)	5182118	6005787	3412.3	Pallars Sobirà (PalS)	557151	565576	203.0
Bages (Bag)	7609029	6271304	5790.1	Pla de l'Estany (PlaE)	1390103	1442415	1116.4
Baix Camp (BaiC)	9821710	5573863	5705.7	Pla d'Urgell (PlaU)	1684890	4169719	1352.2
Baix Ebre (BaiEbr)	3414757	4655762	2210.0	Priorat (Pri)	347558	133327	206.1
Baix Empordà (BaiEm)	10749300	5741767	3623.3	Ribera d'Ebre (Rib)	997496	2944806	1606.9
Baix Llobregat (BaiL)	34192024	23162533	32067.7	Ripollès (Rip)	1131161	1110032	744.2
Baix Penedès (BaiP)	6804378	1949171	2305.7	Segarra (Segr)	863188	2685024	950.8
Barcelonès (Barc)	87617832	34631711	103940.1	Segrià (Segi)	9911298	7487500	7595.5
Berguedà (Berg)	1489310	1057962	1242.7	Selva (Sel)	9031113	8730934	5553.4
Cerdanya (Cer)	1412914	2053735	512.0	Solsonès (Sol)	568287	704048	427.3
Conca de Barberà (Con)	741923	647465	725.2	Tarragonès (Tar)	13214891	40877304	10388.4
Garraf (Garf)	7899473	2482153	3540.9	Terra Alta (TerA)	408164	203401	369.6
Garrigues (Garr)	724839	1031376	503.4	Urgell (Urg)	1599319	1253057	1244.6
Garrotxa (Grot)	2500951	4075751	2108.5	Val d'Aran (ValA)	1391774	928523	363.9
Gironès (Gir)	7972533	7013444	7495.6	Vallès Occidental (ValO)	38687084	22448842	34871.6
Maresme (Mar)	21500298	8071578	11523.4	Vallès Oriental (ValR)	17604767	13078062	15926.0

Barc's performance, other units can focus on refining their input-output relationships and target efficiency scores closer to 1. Conversely, Pri exhibits efficiency scores of 0.5152 under CRS and 1 under VRS in input orientation. The orientation of the SE input reveals suboptimal SE levels, implying that improvements can be made by recalibrating the scale of operation. Slack variables for both input and output are 0, demonstrating that Pri fully utilizes inputs to generate the required level of outputs without any surplus or slack. While Pri is efficient under VRS, inefficiency is observed under CRS, due to scale inefficiency, not operational inefficiency. The gap between CRS and VRS indicates that Pri is not operating at the optimal scale. To attain maximum efficiency under CRS, Pri has the option to either boost the output level by approximately 94% while maintaining constant inputs (as indicated by output orientation) or to reduce input levels by around 48% while keeping outputs unchanged (Fig. 1). This suggests a dual approach for Pri to consider for optimal efficiency. In addition, other units grappling with inefficiency and scale-related challenges can draw valuable insights from Barc's exemplary experiences to position at the efficiency frontier in CRS. Through the strategic enhancement of output levels while keeping inputs unchanged (output-oriented approach) or by decreasing input levels while maintaining constant outputs (input-oriented approach), these units can aim to improve overall efficiency and boost operational effectiveness. Barc's success serves as a beacon for other units, providing a practical roadmap for achieving optimal efficiency and addressing scale-related obstacles within operations.

In both input and output orientation approaches, the DEA model results reveal that BarC and Pri achieve a VRS score equal to 1. This indicates that the utilization of IWC and GDP in these units

is fully efficient. Lambda values are vital for the attainment of allocative efficiency in various units. By harnessing these values, managers and decision-makers can direct units towards improving their efficiency. The lambda values associated with BarC and Pri underscore the heightened sensitivity of DMU efficiency to changes in respective inputs. To enhance overall efficiency, careful management and optimization of these inputs become paramount. Approaches to improvement might focus on maximizing the use of inputs recognized by lambda or examining techniques to decrease or more effectively control these specific inputs, thereby boosting output. Emphasizing these critical factors allows organizations to direct their initiatives towards effectively boosting the performance of DMUs. The emphasis on the lambda values serves as a practical guide for decision-makers, providing a pathway to enhance the overall efficiency of DMUs by addressing and optimizing the critical input factors identified in the analysis (Figs. 2 and 3).

Domestic water consumption

In evaluating the WRCE of the Rib region using an input-oriented DEA model, Considering both CRS and VRS is crucial. Under CRS input orientation, the assumption is that the region operates at an ideal scale, efficiently using DWC to produce the current economic GDP, mirroring findings from studies like those by Ren *et al.* (2017) and Wang *et al.* (2018),

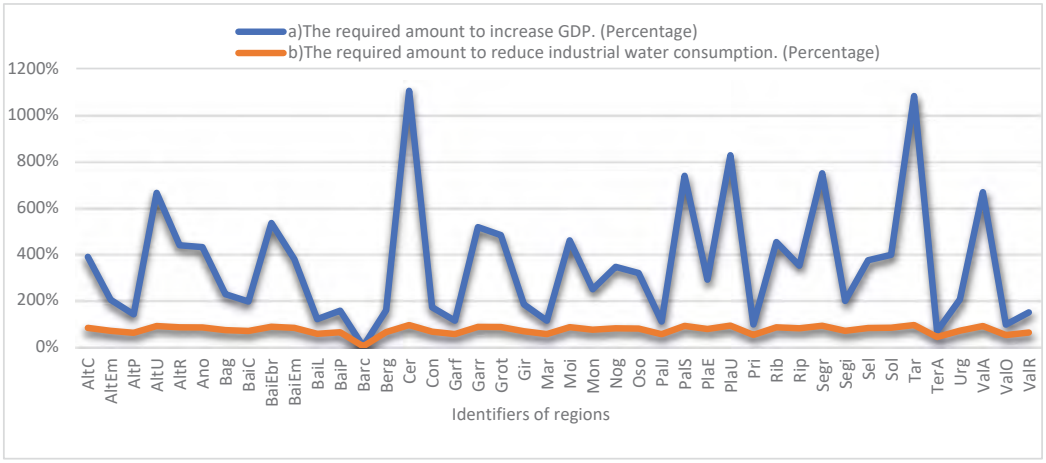


Fig. 1: (a) Maximizing GDP for constant IWC under the CRS framework, using an output-oriented approach. (b) Optimizing IWC for constant GDP under the CRS framework, using an input-oriented approach

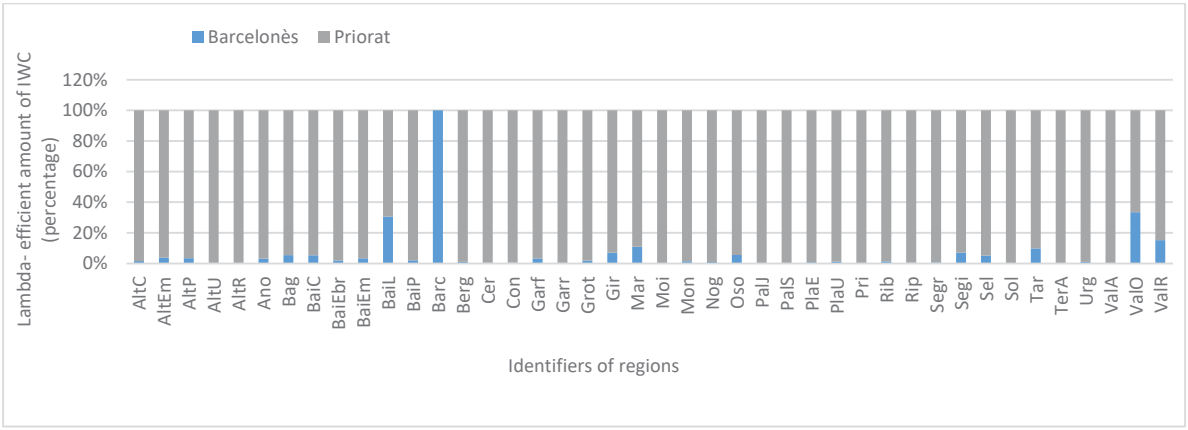


Fig. 2: IWC input orientation: Optimizing DMU efficiency through analysis of lambda values and strategic management

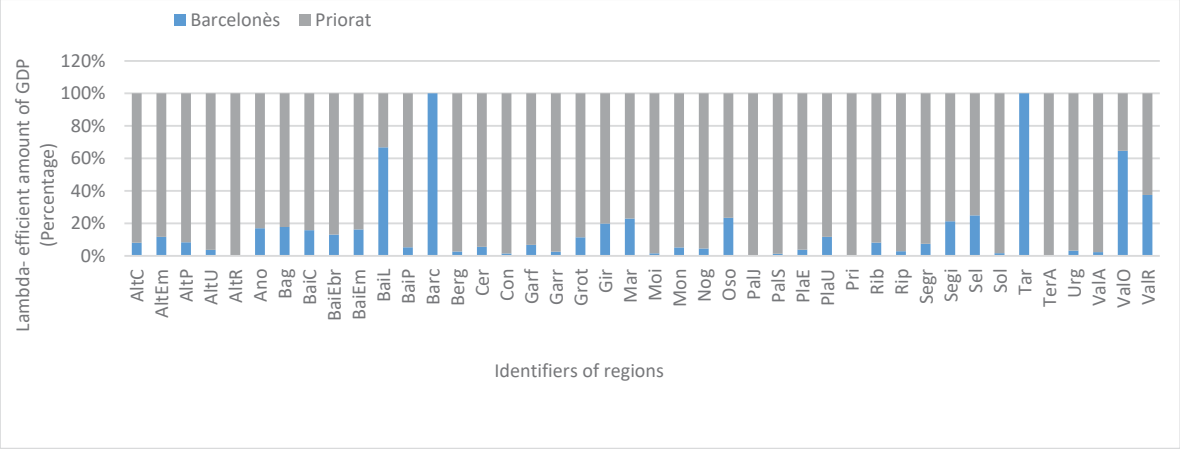


Fig. 3: GDP output orientation: optimizing DMU efficiency through analysis of lambda values and strategic management

which emphasize the importance of optimizing resource utilization. Likewise, within the framework of CRS output orientation, it is presumed that the region operates at an ideal scale, successfully producing economic GDP while ensuring that DWC remains unchanged. In the case of VRS, the analysis explores SE, with a score of 1 indicating the region operates at the perfect scale without underutilizing or overutilizing resources. This insight provides an understanding of potential adjustments in the region's scale of operation while maintaining efficiency. The emphasis on achieving SE equal to 1 underscores the idea that Rib strikes an optimal balance between input utilization and economic output. This comprehensive analysis evaluates not just the efficiency of input consumption but also the relevance of the operational scale, delivering an in-depth understanding of how the region manages inputs, especially DWC, to achieve efficiency and maximize use of resources. Rib serves as a benchmark of optimal input utilization for other units, and the percentage of lambda values corresponding to units provides insights into the efficiency gains achievable. When the lambda values for an efficient unit are substantial, it implies that Rib can achieve notable efficiency gains by minimizing input consumption to approach the optimal levels identified in the benchmark unit. Conversely, lower lambda values suggest that the region is already operating relatively close to the efficiency frontier. By considering efficiency benchmarks and associated lambda values, decision-makers in Rib can gain valuable insights into potential avenues for enhancing input efficiency while maintaining economic output levels. Crafting policies aimed at improving efficiency must prioritize the alignment of environmental advancements with the promotion of social equity and active public involvement (March and Sauri, 2017). This strategy facilitates a deeper and more contextually relevant insight into the improvements in efficiency across the region's economic activities, concentrating on the optimal use of resources. TerA: TerA reveals a CRS efficiency score of 0.5620862, indicating the potential to reduce inputs by approximately 44% while keeping output constant to achieve full efficiency. VRS efficiency is perfect, equal to 1, suggesting no issues with the scale of operation. In output orientation, the CRS efficiency score is 1.779087, indicating that output can be increased by about 78% while keeping inputs constant for full efficiency. Similar to the input-oriented analysis, VRS efficiency is optimal. Notably, TerA is fully efficient in VRS but inefficient in CRS. Pri: From an input-oriented perspective, Pri displays a CRS efficiency score of 0.3681779, suggesting a potential reduction of inputs by approximately 63% while maintaining constant output for achieving full efficiency. The VRS efficiency is perfect, equal to 1, indicating no issues with the scale of operation. With a CRS output-oriented efficiency score of 2.716078, there is an implication of a 172% rise in output, assuming that input levels remain unchanged for maximum efficiency. Similar to the input-oriented analysis, VRS efficiency is optimal.

Noteworthy is that Pri is fully efficient in VRS but inefficient in CRS. The disparity between the CRS and VRS scores indicates that although TerA and Pri are effectively managing resources at their current scale, this approach does not align with the optimal input-output relationships expected under CRS. Ultimately, the gap between the current scale and the optimal scale arises from scale inefficiency, which is caused by a mismatch between the current operational size and the optimal production level. Barc: Evaluating Barc within an input-oriented framework indicates a CRS efficiency score of 0.7363824. This suggests that inputs could potentially be reduced by around 26% while maintaining the same level of output to reach full efficiency. The VRS efficiency is perfect, equal to 1, indicating no issues with the scale of operation. Barc is fully efficient in VRS but inefficient in CRS, due to scale inefficiency, not operational inefficiency. The gap between CRS and VRS indicates that Barc is not operating at the optimal scale. The CRS output-oriented efficiency score is 1.35799, suggesting an increase in output by about 36% while keeping inputs constant for full efficiency. Similar to the input-oriented analysis, VRS efficiency is optimal (Fig. 4).

In the VRS scenario, where four units, including Rib, TerA, Pri, and Barc, are efficient, the focus is on leveraging efficiency to benefit other units. Analyzing the percentage of lambda values linked to these efficient units within the input-oriented DEA model reveals that the inputs of Rib, TerA, Pri, and Barc can act as benchmarks for enhancing efficiency in other units. Conversely, in the output-oriented DEA model, the lambda values associated with Rib, TerA, Pri, and Barc indicate that the economic outputs are already operating efficiently given current input consumption. The efficiencies achieved in these outputs can serve as a source of guidance and motivation for other units aiming to improve their economic productivity. The percentage of the lambda values associated with the units becomes a valuable metric for other units to gauge the potential improvement in output efficiency. By investigating the lambda values in both input and output orientations for these four units, the aim is to promote efficiency enhancements in other units. Rib, TerA, Pri, and Barc can act as benchmarks for optimizing input and output efficiency, serving as examples for other units to emulate and improve overall performance (Figs. 5 and 6).

Industrial and domestic water consumption

The CRS analysis reveals that both Rib and Barc exhibit efficiency scores equal to 1, indicating full efficiency in both input and output orientations. Furthermore, the efficiency scores of the VRS are ideal, reaching a value of 1, which indicates that the operations are functioning at an optimal scale. The high efficiency of Rib can be largely attributed to the reliable water supply sourced from the Ebro river basin. Additionally, the study by Dehghan-Souraki *et al.* (2024) highlights the importance of sediment

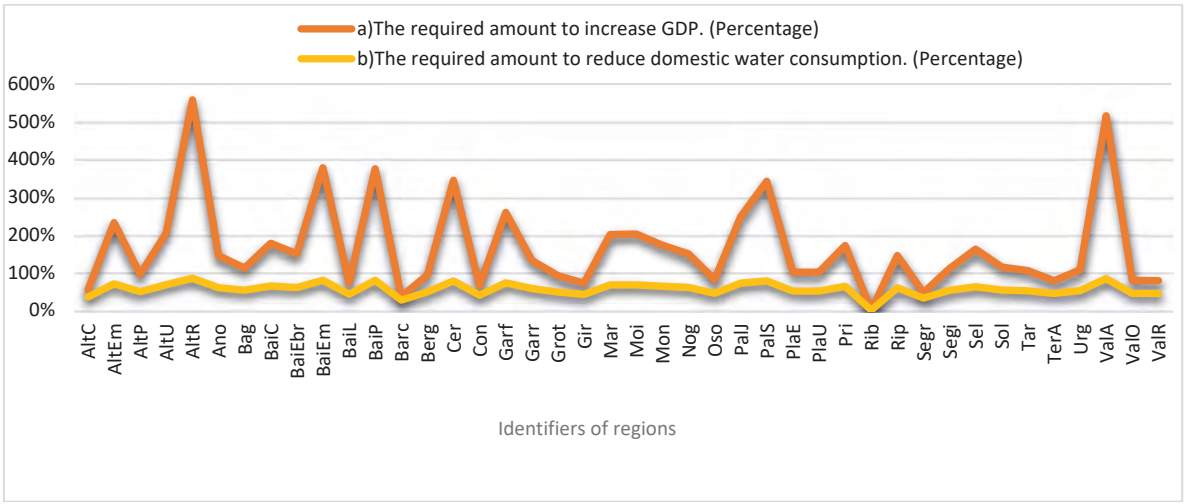


Fig. 4: (a) Maximizing GDP for constant DWC under the CRS framework, using an output-oriented approach. (b) Optimizing DWC for constant GDP under the CRS framework, using an input-oriented approach

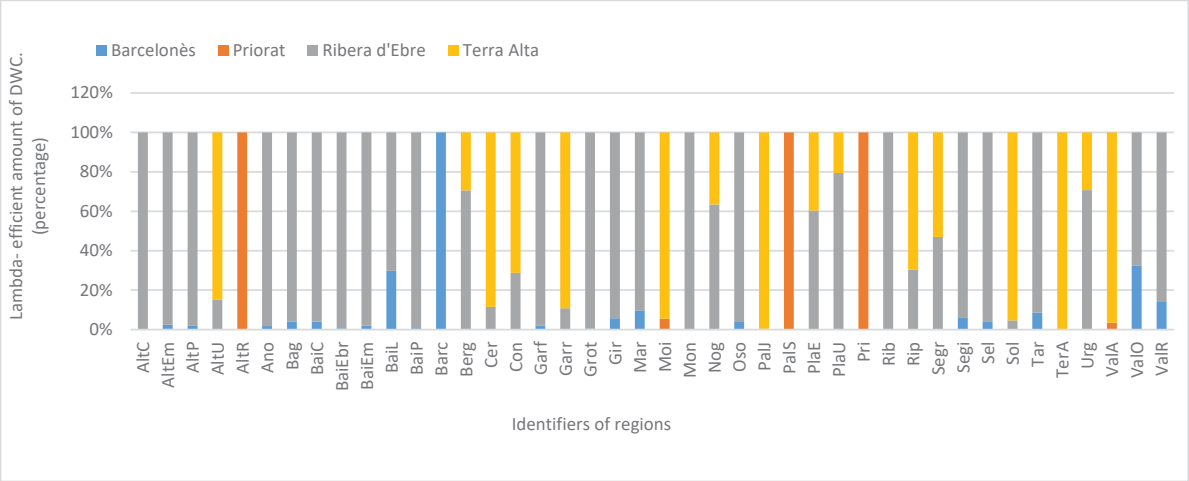


Fig. 5: Domestic consumption input orientation: optimizing DMU efficiency through analysis of values in VRS and strategic management

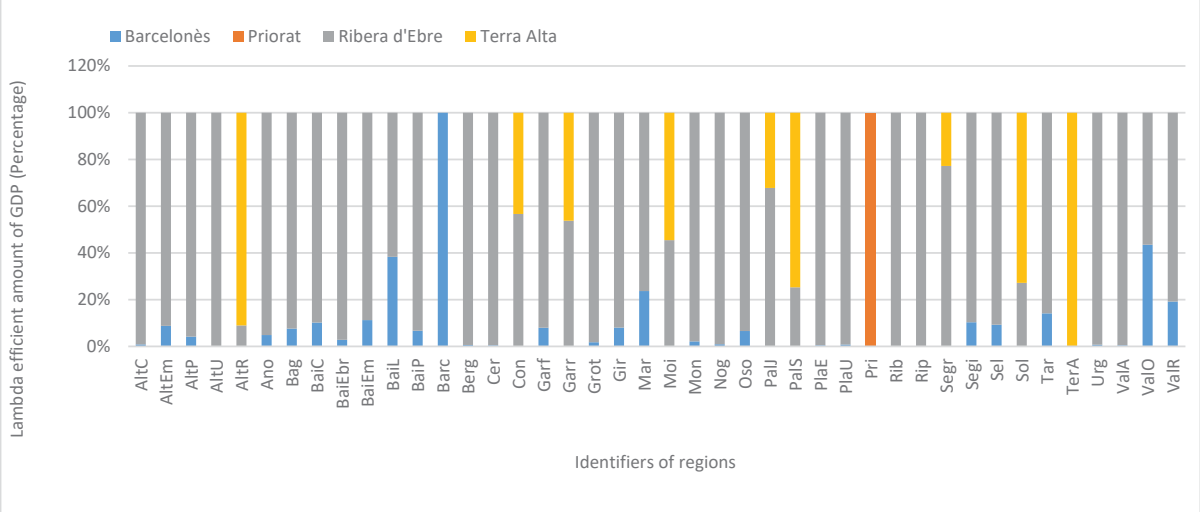


Fig. 6: GDP output orientation: optimizing DMU efficiency through analysis of values in VRS and strategic management

Fig. 4: dynamics and optimization methods, which can impact the overall efficiency of WR management. This aligns with these findings in the DEA analysis, where effective resource allocation and management strategies contribute to the high efficiency observed in Rib. The remarkable efficiency demonstrated by Rib and Barc positions them as exemplary models, setting a standard for other units to follow. Units striving to achieve efficiency in CRS can learn from these exemplars. In an input-oriented approach, different units can reduce industrial and domestic consumption of water inputs simultaneously while maintaining constant GDP to reach the efficiency frontier in CRS. Likewise, adopting an output-oriented framework enables units to boost GDP without altering input levels, thus conforming to the efficiency frontier in CRS, as depicted in Fig. 7. The findings suggest that Rib and Barc set the standard for optimal operations, and other units have the opportunity to enhance efficiency by learning from these exemplary practices.

This chart offers a comparative analysis between current IWC and DWC and efficient input levels while maintaining the GDP constant (Fig. 8). The objective

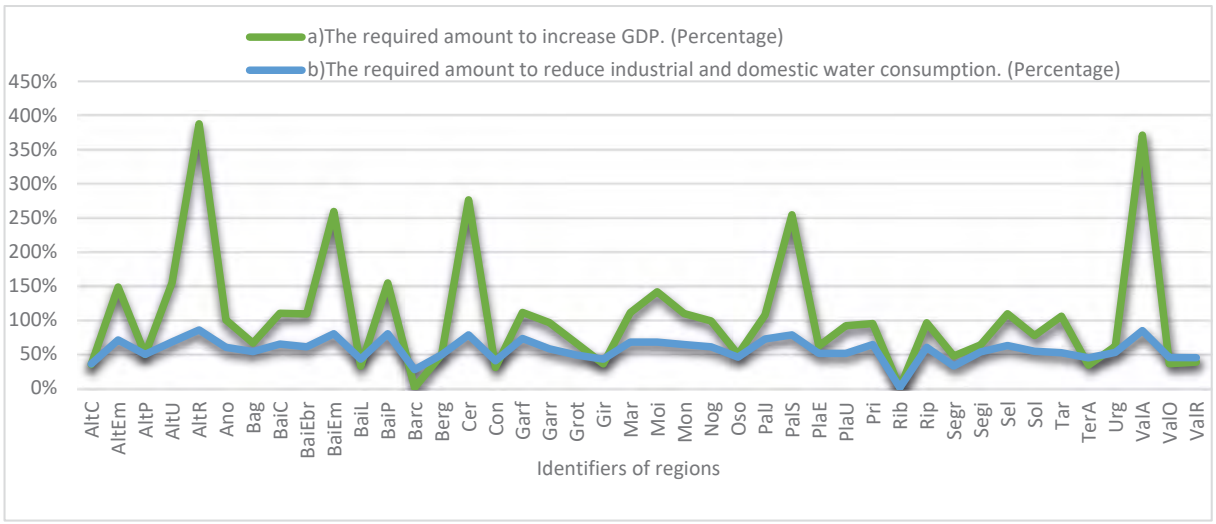


Fig. 7: (a) Maximizing GDP for constant IWC and DWC under the CRS framework, using an output-oriented approach. (b) Optimizing IWC and DWC for constant GDP under the CRS framework, using an input-oriented approach

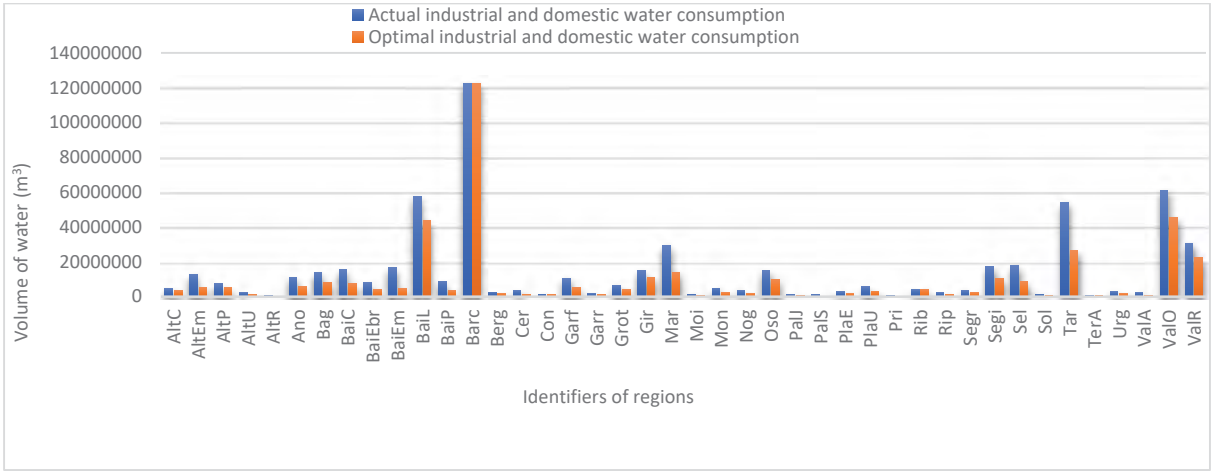


Fig. 8: Comparative analysis of IWC and DWC: current input levels versus efficient input levels with constant GDP output

is to visually emphasize the potential for enhancing resource efficiency to attain stability in economic performance. Included in the chart are visualizations of the present input levels as well as the efficient input levels calculated through the DEA model. The latter signifies the optimal quantities of industrial and domestic consumption water required to sustain a constant level of GDP, thus serving as a benchmark for achieving maximum efficiency. The data presented in the chart can assist units in recognizing areas where resource utilization may be improved. Deviations from the efficient input levels indicate the extent to which units can optimize input consumption without compromising the stability of output. For example, Barc and Rib are efficient in the CRS model, meaning current water consumption aligns with optimal levels. In contrast, the BaiL region has a CRS efficiency score of 0.7605473, indicating a current consumption of 57354557 cubic meters . To achieve optimal consumption, a reduction is necessary, calculated as; (1−0.7605473)*57354557. Fig. 8 illustrates the significant reductions in current water consumption required for each region, assuming constant GDP. Decision-makers can leverage the insights from this

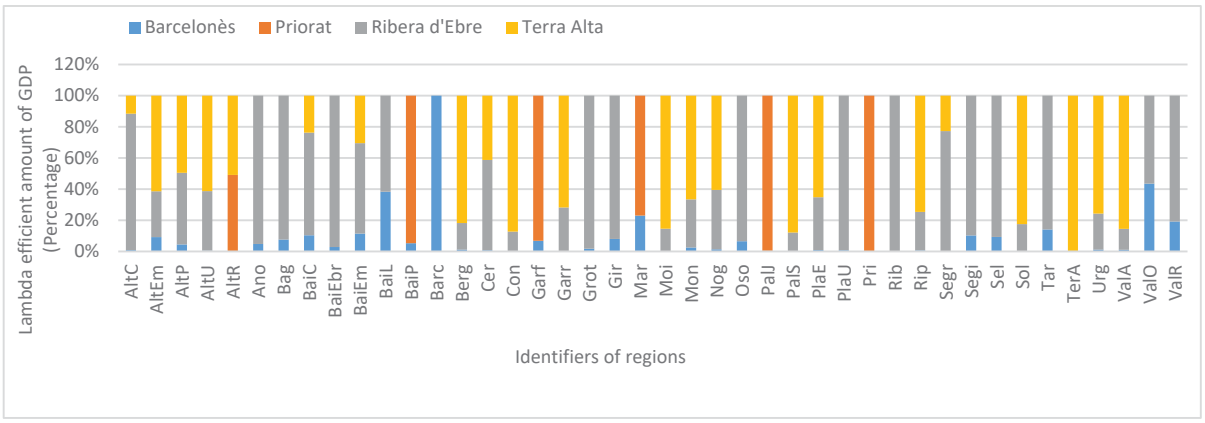


Fig. 9: GDP output orientation keeps IWC and DWC constant: optimizing DMU efficiency through analysis of values in VRS and strategic management

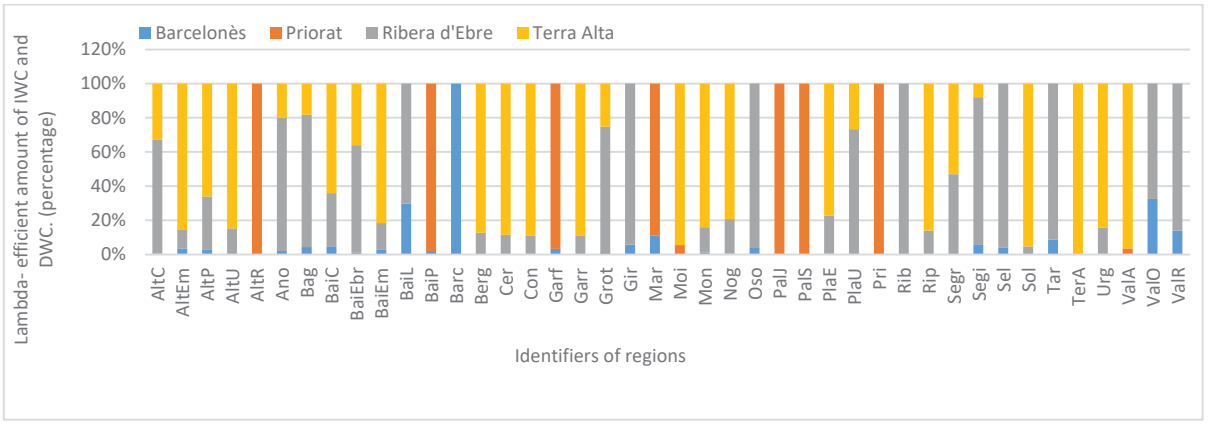


Fig. 10: IWC and DWC input orientation: optimizing efficiency through values in VRS and strategic management

chart as a visual reference to assess and compare the existing input levels against those that are deemed efficient. By synchronizing input levels with established efficiency standards, organizations can improve resource utilization, lower expenses, and support the overall stability of economic performance. In summary, this chart provides practical insights for decision-makers seeking to optimize input levels and promote economic output stability.

This exploration delves into the synergy between VRS scores and lambda values, particularly in units such as TerA, Rib, Pri, and Barc, resonates with research by Hsieh *et al.* (2019) and Geng *et al.* (2019), highlighting the importance of enhancing allocative efficiency to foster sustainable resource management. With VRS scores uniformly set at 1, these units demonstrate operational efficiency and establish excellent standards for effective resource utilization. To illustrate this synergy, Conca de Barc is examined as an illustrative example. With a current IWC and DWC of 1389388 and a VRS score of 0.8875317, the resulting efficient input level is calculated as 1233126. Further efficiency is derived by incorporating lambda values associated with water consumption in Barc (0.21364661% * 122249543), Rib (10.85902% * 3942302), and TerA (88.92733% * 611565). The findings of this analysis reveal that units can harmonize their practices with the efficiency benchmarks outlined by the aforementioned units by engaging in cross-regional cooperation, which enhances sustainable and effective resource utilization (Figs. 9 and 10).

CONCLUSION

In conclusion, the study of WRCE in Catalonia emphasizes the vital significance of sustainable

resource management and corroborates findings from prior research. Focusing on IWC and DWC and GDP, Barc and Rib showcase exceptional efficiency, serving as a benchmark for other units, and guiding units toward the efficiency frontier by leveraging a percentage of the CRS score. Additionally, Furthermore, the VRS analysis brings attention to the experiences of TerA, Pri, Barc, and Rib, stressing the critical role of improving allocative efficiency in advancing sustainable resource management. Leveraging VRS scores, lambda values, and insights from efficient units can enhance management processes, optimize water usage, and adopt best practices. Based on the results of IWC, full efficiency is exhibited by Barc despite water being sourced from internal basins. In contrast, when considering DWC as an input, Rib exhibits full efficiency with water sourced from the Ebro River basin. This implies that the successful management of WRs, whether sourced internally or externally, can contribute significantly to increased efficiency and economic advancement. Also, when DWC is considered as an input, besides Pri, Barc, and TerA are also exhibit efficiency across different scales. Approximately 65% of the regions analyzed demonstrate efficiency scores indicative of potential improvements, reflecting the urgency highlighted in previous studies. The subpar performance associated with the CRS model emphasizes the importance of refining planning strategies, implementing management reforms, and scaling operations effectively. Additionally, when IWC is used as an input, the Pri region demonstrates inefficiency in the CRS model, which assesses overall system efficiency without regard to size and scale. However, the VRS model, which takes scale variations into account, shows that Pri is efficient. Regions that demonstrate efficiency in the VRS model yet reveal inefficiencies in the CRS model need a comprehensive analysis to identify scale inefficiencies and optimize resource allocation. Addressing this gap requires adjustments in scale, better resource allocation, and management reforms to achieve optimal efficiency under CRS, thereby enhancing overall performance and sustainability. The challenges are compounded by inadequate management systems and a deficiency in planning, underscoring the importance of strategic interventions. Key strategies for enhancing WRCE include implementing region-specific policies to improve SE, such as incentivizing sustainable practices and updating allocation frameworks. Advocating for cutting-edge water management technologies can enhance resource efficiency and minimize waste. Establishing cooperative ecosystem models among municipalities, water agencies, and regional authorities is beneficial. Investing in facilities that enable water recycling and reuse within industries can minimize freshwater consumption and improve overall resource efficiency. This not only conserves water but can also lower operational costs, contributing positively to GDP. Moreover, the integration of smart metering systems for urban and industrial users enables the analysis of water consumption behaviors and the identification of areas where efficiency can be improved. Furthermore, awareness campaigns play a pivotal role in promoting water efficiency by raising public awareness, providing knowledge, and encouraging behavior change, ensuring that sustainable practices are adopted across all sectors, including appropriate urban water consumption. Incorporating these strategies into the policymaking process is essential for achieving alignment with global sustainability objectives. By addressing inefficiencies and fostering collaboration, Catalonia can enhance WRCE, promote sustainable growth, and ensure a resilient future. This study employed information gathered from a reliable and readily available source. However, reliance on a specific time period may limit the reflection of long-term changes in efficiency and WR management. Therefore, future research should utilize multi-year data to explore long-term effects. Additionally, the impact of population density on water efficiency should be examined, the role of integrated water management policies should be explored, and additional economic indicators should be included. Considering policy strategies including dynamic water pricing could contribute to resolving inefficiencies and optimizing resource distribution. Other critical areas for investigation include detailed recommendations on policy measures, technological interventions, and governance strategies. Research should focus on understanding the underlying causes of regional efficiency differences, the influence of water-intensive industries on resource management, and the role of agricultural practices in sustainability. Analyzing the influence of water pricing and regulatory measures, alongside the inclusion of cultural elements and behavioral insights in efficiency enhancement

initiatives, as well as reviewing feedback systems for continuous assessment, will greatly reinforce the results obtained. Finally, aligning this research with international standards and examining the environmental trade-offs associated with increased WRCE can provide a comprehensive perspective on sustainable water management.

AUTHOR CONTRIBUTIONS

Z. Bayat contributed to the study conception and design, data collection, analysis and interpretation of results, and draft manuscript preparation. Critical revision of the manuscript for important intellectual content was conducted by J. Vives Costa. Administrative, technical, and material support were provided by J.J. de Felipe Blanch. All authors have reviewed and approved the final manuscript and consent to the submission.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution, and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
$US	United states dollars
AltC	Alt Camp
AltEm	Alt Empordà
AltP	Alt Penedès
AltU	Alt Urgell
AltR	Alta Ribagorça
Ano	Anoia
Bag	Bages
BaiC	Baix Camp
BaiEbr	Baix Ebre
BaiEm	Baix Empordà
BaiL	Baix Llobregat
BaiP	Baix Penedès
BarC	Barcelonès
Berg	Berguedà
BCC	Banker, Charnes, and Cooper
Cer	Cerdanya
Con	Conca de Barberà
CCR	Charnes, Cooper, and Rhodes
CRS	Constant return to scale
DEA	Data envelopment analysis
DWC	Domestic water consumption
DMU	Decision-making unit
Eq.	Equation
Fig.	Figure
Garf	Garraf
Garr	Garrigues
Grot	Garrotxa
Gir	Gironès
GDP	Gross domestic product
IWC	Industrial water consumption
m^3	Cubic meter
Mar	Maresme
Moi	Moianès
Mon	Montsià
Nog	Noguera
Oso	Osona
PalJ	Pallars Jussà
PalS	Pallars Sobirà

PlaE	Pla de l'Estany
PlaU	Pla d'Urgell
Pri	Priorat
PTE	Pure technical efficiency
Rib	Ribera d'Ebre
Rip	Ripollès
SFA	Stochastic frontier analysis
Segr	Segarra
Segi	Segrià
Sel	Selva
Sol	Solsonès
SE	Scale efficiency
Tar	Tarragonès
TerA	Terra Alta
Urg	Urgell
TE	Technical efficiency
ValA	Val d'Aran
ValO	Vallès Occidental
ValR	Vallès Oriental
VRS	Variable return to scale
WR	Water resource
WRCE	Water resource consumption efficiency

REFERENCES

Agencia Catalana de l'Aigua, (2022). Estudi de volums d'aigua subministrats i captats a catalunya. Barcelona, Spain.

Ali, M.K.; Klein, K.K., (2014). Water use efficiency and productivity of the irrigation districts in southern Alberta. Water Resour. Manage., 28(10): 2751-2766 **(16 pages)**.

Azad, M.A.S.; Ancev, T.; Hernández-Sancho, F., (2015). Efficient water use for sustainable irrigation industry. Water Resour. Manage., 29: 1683-1696 **(14 pages)**.

Banker, R.D.; Charnes, A.; Cooper, W.W., (1984). Some models for estimating technical and scale inefficiencies in data envelopment analysis. Manage. Sci., 30: 1078-1092 **(15 pages).**

Bonfiglio, A.; Arzeni, A.; Bodini, A., (2017). Assessing eco-efficiency of arable farms in rural areas. Agric. Syst., 151: 114-125 **(12 pages)**.

Bian, Y.; Yan, S.; Xu, H., (2014). Efficiency evaluation for regional urban water use and wastewater decontamination systems in China: a DEA approach. Resour. Conserv. Recycl., 83: 15-23 **(9 pages)**.

Chen, J.D.; Song, M.L.; Xu, L., (2015). Evaluation of environmental efficiency in China using data envelopment analysis. Ecol. Indic., 52: 577-583 **(7 pages)**.

Coelli, T.; Rahman, S.; Thirtle, C., (2002). Technical, allocative, cost and scale efficiencies in Bangladesh rice cultivation: A non-parametric approach. J. Agric. Econ., 53(3): 607-626 **(20 pages)**.

Coelli, T., (1996). A guide to DEAP version 2.1: a data envelopment analysis (computer program). CEPA working papers no. 8/96. University of new england, Australia.

Coelli, T.J.; Rao, P.D.S.; O'Donnell, C.J.; Battese, G.E., (2005). An introduction to efficiency and productivity analysis. 2nd Ed. Springer, New York.

Cai, X.M.; Yang, Y.C.E.; Ringler, C.; Zhao, J.S.; You, L.Z., (2011). Agricultural water productivity assessment for the yellow river basin. Agric. Water Manage., 98: 1297-1306 **(10 pages)**.

Charnes, A.; Cooper, W.W.; Rhodes, E., (1978). Measuring the efficiency of decision-making units. Eur. J. Oper. Res., 2: 429-444 **(16 pages)**.

Dehghan-Souraki, D.; López-Gómez, D.; Bladé-Castellet, E.; Larese, A.; Sanz-Ramos, M., (2024). Optimizing sediment transport models by using the Monte Carlo simulation and deep neural network (DNN): A case study of the Riba-Roja reservoir. Environ. Modell. Software. 175, 105979 **(15 pages)**.

Farrell, M.J., (1957). The measurement of productive efficiency. J. R. Stat. Soc. Ser. A, 120(III): 253-281 **(29 pages)**.

Frija, A.; Chebil, A.; Speelman, S.; Buysse, J.; Van Huylenbroeck, G., (2009). Water use and technical efficiencies in horticultural greenhouses in Tunisia. Agric. Water Manage., 96: 1509-1516 **(8 pages)**.

Frija, A.; Wossink, A.; Buysse, J.; Speelman, S.; Van Huylenbroeck, G., (2011). Irrigation pricing policies and its impact on agricultural inputs demand in Tunisia: a DEA-based methodology. J. Environ. Manage., 92: 2109-2118 **(10 pages)**.

Gadanakis, Y.; Bennett, R.; Park, J.; Areal, F.J., (2015). Improving productivity and water use efficiency: a case study of farms in England. Agric. Water Manage., 160: 22-32 **(11 pages)**.

Geng, Q.; Ren, Q.; Nolan, R.H.; Wu, P.; Yu, Q., (2019). Assessing China's agricultural water use efficiency in a green-blue water perspective: a study based on data envelopment analysis. Ecol. Indic., 96: 329-335 **(7 pages)**.

Government of Catalonia, (2022). Summary of the 2021 annual report of the Catalan economy. Ministry of the economy and finance, Barcelona, Spain.

Gungor-Demirci, G.; Lee, J.; Keck, J., (2018). Assessing the performance of a California water utility using two-stage data envelopment analysis. J. Water Resour. Plann. Manage., 144: 1-9 **(9 pages)**.

Han, M.; Ren, Q.; Wang, Y.; Du, J.; Hao, Z.; Sun, F.; Cheng, L.; Qi, S.; Li, D., (2013). Integrated approach to water allocation in river basins. J. Water Resour. Plann. Manage., 139(2): 159-165 **(7 pages)**.

Hsieh, J.-C.; Ma, L.-H.; Chiu, Y.-H., (2019). Assessing China's use efficiency of water resources from the resampling super data envelopment analysis approach. Water. 11(5): 1069: 1-15 **(15 pages)**.

Hu, F.; Tan, D., (2018). Water risk report. No water, no growth—does Asia have enough water to develop?. China water risk., Hong Kong, China.

Idescat, (2023). Territorial gross domestic product (GDP) 2021.

Langsdale, S.M.; Beall, A.; Carmichael, J.; Cohen, S.J.; Forster, C.B., (2007). An exploration of water resources futures under climate change using system dynamics modeling. Integrated Assessment Journal., 7(1), 51–79 **(30 pages)**.

Medrano, H.; Tomas, M.; Martorell, S.; Escalona, J.; Pou, A.; Fuentes, S.; Flexas, J.; Bota, J., (2015). Improving water use efficiency of vineyards in semi-arid regions: a review. Agron. Sustainable Dev., 35(2): 499-517 **(19 pages).**

Mardani, A.; Streimikiene, D.; Balezentis, T.; Saman, M.Z.M.; Nor, K.M.; Khoshnava, S.M., (2018). Data envelopment analysis in energy and environmental economics: an overview of the state-of-the-art and recent development trends. Energies. 11(8), 2002: 1-21 **(21 pages).**

Manjunatha, A.V.; Speelman, S.; Chandrakanth, M.G.; Van Huylenbroeck, G., (2011). Impact of groundwater markets in India on water use efficiency: a data envelopment analysis approach. J. Environ. Manage., 92: 2924-2929 **(6 pages).**

Mohtashami, A., Al Ghafri, A., Akbarpour, A., (2024). Computation of minimum adjustment factors for sustainable groundwater management using data assimilation and Vensim dynamic model. Paddy Water Environ., 22(3), 431–447 **(17 pages)**.

March, H.; Sauri, D., (2017). When sustainable may not mean just: A critical interpretation of urban water consumption decline in Barcelona. Local Environ., 22(5): 523–535 **(13 pages)**.

Pascual-Pañach, J.; Sánchez-Marrè, M.; Cuguero-Escofet, M.A., (2024). A temporal case-based reasoning approach for performance improvement in intelligent environmental decision support systems. Eng. Appl. Artif. Intell., 136, 108833 **(15 pages)**.

Qin, H.; Zheng, C.; He, X.; Refsgaard, J.C., (2019). Analysis of water management scenarios using coupled hydrological and system dynamics modeling. Water Resour. Manage., 33(12), 4849–4863 **(15 pages)**.

Ren, C.; Li, R.; Guo, P., (2017). Two-stage DEA analysis of water resource use efficiency. Sustainability. 9(1): 1-17 **(17 pages)**.

Rodríguez Díaz, J.A.; Camacho Poyato, E.; López Luque, R., (2004). Application of data envelopment analysis to studies of irrigation efficiency in Andalusia. J. Irrig. Drain. Eng., 130(3): 175-183 **(9 pages)**.

Rousta, M.J.; Matinizadeh, M.; Zarafshar, M.; Nouri, E., (2023). Spate irrigation slightly ameliorates an arid soil's quality, but tree planting enhances its characteristics. Soil Tillage Res., 229: 105658 **(11 pages)**.

Soltanjalili, M.; Bozorg-Haddad, O.; Marino, M.A., (2013). Operating water distribution networks during water shortage conditions using hedging and intermittent water supply concepts. J. Water Resour. Plann. Manage., 139(6): 644-659 **(16 pages)**.

Speelman, S.; D'Haese, M.; Buysse, J.; D'Haese, L., (2008). A measure for the efficiency of water use and its determinants: a case study of small-scale irrigation schemes in north-west province, South Africa. Agric. Syst., 98(1): 31-39 **(9 pages)**.

Susnik, J.; Vamvakeridou-Lyroudia, L.S.; Savic, D.A.; Kapelan, Z., (2013). Integrated modelling of a coupled water-agricultural system using system dynamics. J. Water Clim. Change., 4(3), 209–231 **(23 pages)**.

Susaeta, A.; Adams, D.C.; Carter, D.R.; Dwivedi, P., (2016). Climate change and ecosystem services output efficiency in southern loblolly pine forests. Environ. Manage., 58: 417-430 **(14 pages)**.

Tomohiro, O.; Masataka, W.; Xu, K., (2006). Analysis of water demand and water pollutant discharge using a regional input-output table: an application to the city of Chongqing, upstream of the Three Gorges Dam in China. Ecol. Econ., 58: 221-237 **(17 pages)**.

Tidwell, V.C.; Passell, H.D.; Conrad, S.H.; Thomas, R.P., (2004). System dynamics modeling for community-based water planning: Application to the Middle Rio Grande. Aquat. Sci., 66(4): 357–372 **(16 pages)**.

World Economic Forum, (2014). Global risks report., 9th Ed.

Wang, S.; Zhou, L.; Wang, H.; Li, X., (2018). Water use efficiency and its influencing factors in China: based on the data envelopment analysis (DEA)—Tobit model. Water. 10(6): 1-16 **(16 pages)**.

AUTHOR (S) BIOSKETCHES

Bayat, Z., Ph.D. Candidate, Department of Mining, Industrial and ICT Engineering (Industrial Technologies). E.P.S.E. Manresa, Universitat Politécnica de Catalunya (UPC), Barcelona, Spain.
- Email: *zahra.bayat@upc.edu*
- ORCID: 0009-0008-4011-640X
- Web of Science ResearcherID: LRC-7867-2024
- Scopus Author ID: NA
- Homepage: https://futur.upc.edu/ZahraBayat

Vives Costa, J., Ph.D., Professor, Department of Mining, Industrial and ICT Engineering (Industrial Technologies). E.P.S.E. Manresa, Universitat Politécnica de Catalunya (UPC), Barcelona, Spain.
- Email: *jordi.vives@upc.edu*
- ORCID: 0000-0003-3854-775X
- Web of Science ResearcherID: AAD-5672-2020
- Scopus Author ID: 57209327674
- Homepage: https://futur.upc.edu/JordiVivesCosta

de Felipe Blanch, J.J., Ph.D., Professor, Department of Mining, Industrial and ICT Engineering (Industrial Technologies). E.P.S.E. Manresa, Universitat Politécnica de Catalunya (UPC), Barcelona, Spain.
- Email: *jose.juan.de.felipe@upc.edu*
- ORCID: 0000-0002-7758-3967
- Web of Science ResearcherID: ACO-6940-2022
- Scopus Author ID: 57193425828
- Homepage: https://futur.upc.edu/JoseJuandeFelipeBlanch

HOW TO CITE THIS ARTICLE

Bayat, Z.; J. Vives Costa, J.; de Felipe Blanch, J.J., (2025). Optimizing industrial and domestic water consumption efficiency for sustainable growth through data envelopment analysis. Global J. Environ. Sci. Manage., 11(2): 481-496.

DOI: 10.22034/gjesm.2025.02.07

URL: https://www.gjesm.net/article_720132.html

Global J. Environ. Sci. Manage. 11(2): 497-518, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Innovation in the blue economy and environmental sustainability in marine and fisheries strategy

S.W. Trenggono[1,2], I. Meilano[1,*], H. Latief[1], S.D. Diantara[1,4], W.I. Sakti[1,3], D.G.K. Ketaren[1], I.N.P. Winata[1], T. Yuwono[1,2], Syamdidi[1,2], F.Y. Arthatiani[1,2], K. Kasim[1,2], I.N. Radiarta[2]

[1] *Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Bandung, Indonesia*

[2] *Ministry of Marine Affairs and Fisheries, Gedung Mina Bahari, Jl. Merdeka Timur, Gambir, Jakarta Pusat, Indonesia*

[3] *Universitas Tarumanagara, Jalan Letjen S. Parman, Grogol Petamburan, Jakarta Barat, DKI Jakarta, Indonesia*

[4] *Ministry of Defense, Jalan Budi Kemulyaan, Jakarta Pusat, DKI Jakarta, Indonesia*

ARTICLE INFO

Article History:
Received 29 August 2024
Revised 20 November 2024
Accepted 01 January 2025

Keywords:
Blue economy
Environmental sustainability
Fisheries
Sustainable aquaculture

ABSTRACT

BACKGROUND AND OBJECTIVES: The Ministry of Marine Affairs and Fisheries of Indonesia has introduced its blue economy framework to promote sustainable use of marine and fishery resources while ensuring ecosystem protection. This study investigates five major programs initiated by the Ministry that concentrate on ecological sustainability and the effective use of Indonesia's marine biodiversity: expanding marine conservation areas, implementing a quota-based fisheries system, monitoring coastal and small island regions, advancing sustainable aquaculture, and addressing marine plastic pollution. This study focuses on the application of the Ministry's fisheries Blue Economy initiatives, seeking to establish future strategies derived from the experiences accumulated during two years of operation.
METHODS: To assess the implementation of these key initiatives, participatory approaches, including focus group discussions, semi-structured interviews, and key informant interviews, were utilized to gather insights into program implementation experiences and lessons learned. In-person interviews were performed utilizing a blend of closed and open-ended questions. The focus was on key informants, which comprised representatives from four Directorate Generals, seven unit coordinators, non-governmental organization members, and participants from fishermen groups. Following a pre-test and subsequent revisions, the final questionnaire was finalized with 25 questions. These covered topics such as knowledge of the Ministry's five key initiatives, understanding of regulatory enforcement, perceptions of blue economy management, and suggestions for future strategies
FINDINGS: The implementation of quota-based fisheries system, known as Penangkapan Ikan Terukur, has demonstrated significant progress, particularly in fisheries management area 718, where increased vessel landings have minimized the need for transporting catches back to Java. The expansion of marine conservation initiatives has led to the establishment of protected areas totaling 97.5 million hectares. Nevertheless, there are ongoing challenges in effectively linking these areas, largely attributed to their vast expanse and insufficient funding. Sustainable aquaculture has been prioritized, achieving a remarkable increase in shrimp farming productivity from 0.6 to 40 tons per hectare per cycle. In addition, the Maritime Intelligent Platform has refined the licensing procedures for marine and fishery activities, resulting in better compliance with regulations. The Ministry's public engagement campaign, "Month of Loving the Sea," has mobilized 2,858 participants over two years, removing nearly 172 tons of plastic waste from the ocean.
CONCLUSION: While challenges such as resource limitations and the need for advanced technology adoption persist, the blue economy initiatives exhibit strong potential for success. Regular monitoring and evaluation play a vital role in tackling these issues, thereby solidifying Indonesia's commitment to the sustainable management of marine resources and the blue economy principles.

DOI: 10.22034/gjesm.2025.02.08

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
58

NUMBER OF FIGURES
5

NUMBER OF TABLES
3

*Corresponding Author:
Email: *meilanoirwan@gmail.com*
Phone: +628139 418 1960
ORCID: 0000-0003-3488-9154

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

The blue economy concept, first endorsed by the World Bank and adopted by many archipelagic countries, has been designed to encourage the responsible and long-term utilization of marine resources, enhance economic development, foster social inclusion, and strengthen livelihoods (World Bank, 2024). With its extensive network of islands and abundant biodiversity, Indonesia is uniquely suited to implement this approach. As the largest archipelagic country on the planet, it consists of more than 17,000 islands that extend around 5,000 kilometers from east to west, representing nearly one-eighth of the Earth's equatorial line. With its extensive coastline of roughly 108,000 kilometers, around 16 percent (%) of the world's coral reefs, habitat to more than 2,000 reef fish species, and situated at the heart of the Coral Triangle, the country is acknowledged as a global hotspot for marine biodiversity. This region, shared with five other countries—Malaysia, Papua New Guinea, the Philippines, the Solomon Islands, and Timor-Leste—represents a critical area for the conservation of marine life on a global scale (World Bank, 2021). The diverse marine resources of Indonesia provide seafood for both domestic markets and export seafood to countries around the globe. The contribution of fishery products to animal protein consumption in Indonesia stands at 60%, emphasizing the country's position as one of the leading nations dependent on fisheries worldwide (Dirhamsyah, 2005). Indonesia's fishery sector plays a vital role in its economy, and it is consistently promoted to expand production, given its importance to local and national economic growth. Consequently, the political support for managing fisheries sustainably is often inconsistent, as it attempts to reconcile the push for higher production with the understanding that fisheries have a restricted capacity for harvesting. In 2022, Indonesia generated roughly 7.448 million tons of marine fish, increasing to 8.188 million tons in 2023 (MMAF, 2024). A study showed that integrating blue economy principles into Indonesia's national policies is paramount to ensure the fair distribution of economic and community benefits while protecting marine resources (Sari and Muslimah, 2020). Likewise, the findings of Kobayashi (2023) reinforces these initiatives, highlighting the necessity for innovative approaches in fisheries management and aquaculture to boost sustainability and economic viability (Fig. 1).

The marine conservation area initiative by the Ministry of Marine Affairs and Fisheries (MMAF) aims to expand from 28.9 million hectares (ha), which currently represents 8.9% of Indonesia's total marine territory, to 97.5 million ha, approximately 30%, by the year 2045 (MMAF, 2023). It stated that the 30% conservation area target in 2045 aligns with Indonesia's broader national goals, aiming to achieve the Indonesia Gold Development Target by 2045. The vision of Indonesia Gold 2045 is a concept that

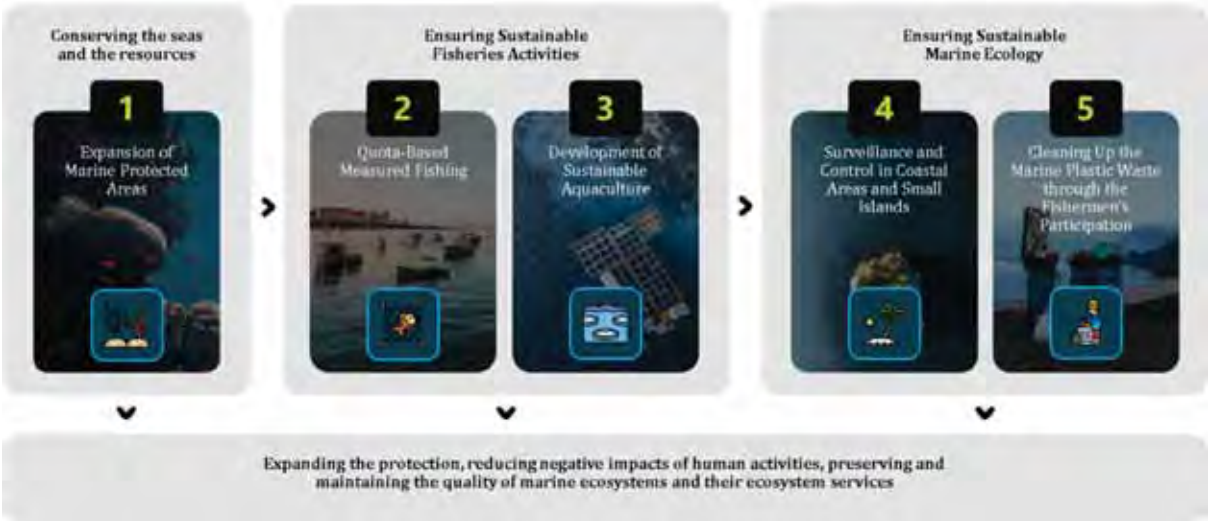


Fig. 1: Blue economy fisheries priority program initiated by The Ministry of Marine Affairs and Fisheries of Indonesia

aspires to make Indonesia a sovereign, advanced, just, and prosperous nation by the year 2045, which coincides with the 100th anniversary of Indonesia's independence. To reach this conservation goal, strategies will focus on bolstering the monitoring and surveillance of marine conservation areas with satellite data, establishing ocean accounting systems, and ensuring that marine protected areas (MPAs) are marked on International Maritime Organization (IMO) maps to shield them from potentially harmful maritime activities (MMAF, 2023). Research by Costello (2024) found clear correlation of MPAs' economic benefits studied from 48 examples of fisheries-related and 31 examples of tourism-related economic benefits across 25 and 24 countries, respectively. The advantages for fisheries encompass a rise in fish numbers, increased catch sizes, improved fishing efficiency, a higher production and dispersal of eggs and larvae, along with the development of larger fish and lobsters. Well-designed and properly managed MPAs provide sustainable advantages to fishing communities, while even less optimal MPAs can still deliver economic benefits. The study determined that MPAs rank among the most efficient strategies for encouraging the sustainable management of marine resources. On the other hand, as Indonesia is also implementing quota-based fishing, this quota mechanism is believed to boost both sustainability and economic efficiency in fisheries when paired with a total allowable catch (TAC) system, which caps the total harvest to avoid overfishing. In Australia, quota-managed fisheries generated around 683 million United States Dollars (USD) in gross production value, making up nearly 60% of Australia's wild-caught fishery output (Pascoe *et al.*, 2022). Based on earlier research demonstrating the benefits of conservation and sustainable fisheries management, the Ministry has rolled out multiple programs to promote a sustainable blue economy for Indonesia's marine resources. The five essential programs are outlined in five initiatives: expanding marine conservation areas, implementing a quota-based fisheries system, promoting sustainable aquaculture practices, regulating and overseeing coastal regions and small islands, and leading a campaign to clean up marine plastics. Indonesia's marine and fisheries policymakers set these priorities to safeguard the health of the nation's oceans and ensure the long-term sustainable use of its aquatic resources and fisheries services (MMAF, 2023). The effective administration of outer and small islands, as well as coastal areas, is vital. This approach promotes equitable distribution of resources and sustains ecological balance, thereby enhancing a blue economy that is advantageous for all stakeholders. A study reported by Puspitasari *et al.* (2023) emphasizes that digital transformation can significantly improve fisheries management and market access, suggesting that modern technologies facilitate more efficient resource management, particularly in remote and isolated regions and among the different scales of fishing effort from small to commercial scale. The application of this technology encourages fosters economic growth while aiding in the conservation of the unique biodiversity present in coastal and island ecosystems, which is vital for maintaining long-term ecological stability. Furthermore, the marine plastics cleanup campaign is crucial for safeguarding biodiversity and human well-being (Khairunnisa, 2022). These five MMAF initiatives need legal framework support as the country's commitment to balancing economic targets while guaranteeing the sustainability of its marine and fishery sectors for future generations. This study examines the implementation of the Ministry's fisheries blue economy initiatives, aiming to formulate future strategies based on lessons learned from two years of execution. This study conducted in Jakarta, Indonesia in 2024.

MATERIALS AND METHODS

To examine Indonesia's Fisheries Blue Economy Programs that firstly initiated by MMAF, it is incorporated the qualitative analysis with evaluations of five key initiatives. The initiative commenced with a thorough analysis of the literature, which included peer-reviewed articles, government documents, and international publications, aimed at obtaining critical information on sustainable approaches to marine management practices. A triangulation method was employed, incorporating a range of participatory tools such as focus group discussions (FGDs), semi-structured interviews, and key informant interviews to gather data on program implementation experiences. The interviews were conducted in person using a mix of closed and open-ended questions, targeting 15 key informants (Kusumawati and Huang, 2015). These included representatives from four Directorate

Generals, seven unit coordinators, two non-government organization (NGO) members, and two members of fishermen groups. The final questionnaire, consisting of 25 questions, was completed after a pre-test and subsequent revisions. These covered topics such as knowledge of the Ministry's five key initiatives, understanding of regulatory enforcement, perceptions of blue economy management, and suggestions for future strategies. The objective of this method was to pinpoint the critical challenges and analyze the outcomes related to the implementation of Indonesia's five essential Blue Economy initiatives. Qualitative responses that extracted from closed-ended questionnaire then tabulated and analyzed using a word frequency query used to capture the nuanced perspectives of stakeholders, and it helped contextualize quantitative results.

RESULTS AND DISCUSSION

Expanding marine conservation areas

Indonesia's marine conservation zones currently cover about 28.29 million ha, roughly 8.9% of the country's total marine area (MMAF, 2023). The plan is to expand these zones to 97.5 million ha, or 30% of our marine territory, by 2045. This target is relevant to a consensus that agreed on the Kunming-Montreal Global Biodiversity Framework, intended to safeguard the long-term viability of fish stocks, protect carbon stocks, and preserve coastal ecosystems and small islands to benefit local communities. To reach the target set for 2045, the country has established a diverse strategy that prioritizes the incorporation of technology, sustainable financial practices, community engagement, and effective enforcement protocols. This approach includes implementing an integrated maritime intelligence platform and plans to launch blue bond financing to support the expansion of MPAs. Furthermore, cutting-edge satellite technology is being leveraged to bolster monitoring efforts across these expansive areas, guaranteeing the efficiency of management and advancement towards the goals. The Indonesian MPAs expansion not only boosts carbon absorption that potentially absorbs 188 million tons of carbon dioxide equivalent (tCO_2eq), but also improves oxygen levels and safeguards crucial habitats such as spawning, nursery, and feeding grounds. The Table 1 outlines the plan for expanding Indonesia's marine reserve areas by 2045 and their potential for carbon sequestration. The planned growth of conservation areas significantly relies on the investment in their planning and enforcement, especially considering that the existing effectiveness of MPAs in Indonesia is still insufficient, as assessed by the monitoring system established by MMAF (White *et al.,* 2021).

The country's initiative to broaden the scope of MPAs plays a vital role in the blue economy framework for fisheries. This expansion is expected to positively impact the livelihoods of coastal communities. Economic analysis shows that conservation areas have led to increased fish catches, resulting in a 6% improvement in the lives of coastal residents (Hastuty *et al.,* 2015). Additionally, stakeholders see the main benefits of these conservation areas as more significant fish quantities (biomass), a rise in tourism, and management practices that incorporate

Table 1: The expansion plan of Indonesia marine conservation areas in 2045 and it potential carbon storage.

Zone	Conservation area (million ha)	Target conservation area (Million ha in 2045)	Carbon absorption potential (tCO2eq)
Zone 1: Karimata Strait, Natuna Sea, and North Natuna Sea	4.8	9.9	32.777.280
Zone 2: Sulawesi Sea, north of Halmahera Island, Cenderawasih Bay waters, and the Pacific Ocean, Open Pacific Ocean Waters	2.9	16.8	24.860.210
Zone 3: Tomini Bay, Maluku, Halmahera, and Seram Sea,Berau Bay, Aru andArafura Sea, eastern Timor Sea waters, Tolo Bay and Banda Sea	11.7	32.2	92.044.300
Zone 4: West Sumatra Indian Ocean, Sunda Strait, South of Java Indian Ocean to Nusa Tenggara southern waters, Sawu Sea, and Timor Sea, and the Open Indian Ocean Waters.	5.7	23.8	4.526.400
Zone 5: Malaka Strait dan Andaman Sea	0.09	1.4	8.241.280
Zone 6: the waters of Java Sea, Makassar Strait waters, waters of Bone Bay, Flores, and Bali Strait	3.1	13.4	18.968.130
Total	28.29	97.5	181.417.600



Fig. 2: The MMAF action plan for expanding its marine conservation areas in six zone by 2045

local wisdom, which all contribute to the overall prosperity of these communities. Fig. 2 illustrate that Indonesia has segmented its marine regions into six zones. The assessment of this division takes into account various criteria, such as maritime security, environmental aspects, nursery and fishing habitats, and the effectiveness of monitoring and surveillance of vessels (Trenggono, 2023).

Numerous studies demonstrate that MPAs contribute to the conservation of fish stocks and biodiversity, both of which are vital for communities that rely on fishing to sustain their livelihoods (Green *et al.*, 2014). However, the success of MPAs often depends on how displaced fishing activities are managed. For example, Klein and Watters (2020) examined the Scotia Sea and found that where displaced fishing efforts are relocated plays a crucial role in whether MPAs protect predators or increase fish catches. Sein (2010) emphasized that early, strategically planned Marine Protected Areas (MPAs) that took into account the displacement of fishing efforts is likely to succeed in meeting their intended objectives. The study of Sein (2010) stressed that MPAs should not be established without carefully balancing the needs of the protected areas with the impacts on prior fishing activities. A recent study by Ziegler (2024) found that various factors affect how well MPAs enhance harvested species' biomass, abundance, and size. Several critical components, including the dimensions of the MPA, its establishment duration, and its connectivity with other MPAs, are essential for determining its overall effectiveness. Additionally, they observed a clear relationship between the size and age of MPAs and improvements in fish catch, biomass, and species response while considering factors like latitude, primary productivity, and proximity to the nearest MPA. According to a recent study conducted by White *et al.* (2021), the creation of interconnected Marine Protected Area Networks has yielded various benefits for the conservation of the ocean. The advantages include preserving diverse habitats and species, reducing local effects of climate change, supporting genetic diversity and the long-term survival of populations. In addition, a study reported by Cusack *et al.* (2021) mentioned a case study of the Moalboal MPA in Philippines demonstrates that active community involvement in managing ecotourism resources, coupled with a network of locally managed MPAs and the equitable distribution of economic benefits within the community, has fostered the growth of a thriving marine ecotourism sector. This MPA case illustrates how MPAs can act as catalysts for marine ecotourism, creating new income opportunities for coastal communities and lessening their dependence on extractive fishing activities in tropical regions. Considering MPAs' advantages, which are promising to protect marine resources based on prior studies and Indonesia contribution to the regional marine conservation movements, the MMAF then initiated to extend the current MPA. Considering the extensive marine zones and current

MPAs in Indonesia, it is crucial to adopt advanced technologies like satellite monitoring for the effective surveillance and management of these regions. By monitoring and regulating the MPAs, it is possible to ensure that fishing does not take place within the reserves, and strict penalties will be applied to those who fail to comply with the regulations. A study conducted by LaRue *et al.* (2020) reported that high-resolution satellite imagery offers a vital tool for monitoring remote and difficult-to-access marine areas, improving the monitoring, management and conservation of MPAs. The findings of the study revealed that sophisticated satellite technology can effectively decrease costs and provide readily available data. This improvement aids in research and monitoring efforts, enabling the observation of species and habitat conditions in large and isolated regions like the Southern Ocean. Besides applying high technology to ensure the efficacy of the marine conservation areas, engaging and educating local communities is an essential factor for empowering them to actively participate in conservation efforts so the objectives of the MPA can be achieved. It is vital to combine community engagement with the use of advanced technology in the implementation of marine conservation strategies to successfully fulfill the goals of the MPA. A case study from the South Australian MPA showed that visual and virtual communication tools helped foster community awareness that helps alter collaboration among communities, eventually strengthening support for MPAs and facilitating long-term conservation benefits (Melissa *et al.,* 2024*)*. An additional example is present Raja Ampat, Indonesia, where the local population has effectively safeguarded its aquatic environment and resources. The Raja Ampat Regional Public Service Agency (BLUD) has successfully engaged local communities to help manage and protect the region's MPAs. The "Jaga Laut" personnel from the BLUD regularly patrol all MPAs in Raja Ampat to monitor suspicious or illegal activities, working closely with local fishers and the Indonesian National Police, the Indonesian Navy, and fisheries investigators. The BLUD not only enforces regulations within MPA zones but also focuses on raising community awareness about conservation, fostering sustainable tourism practices, and boosting the economic benefits derived from conservation efforts for the local residents. Nowadays, Raja Ampat is a well-known marine tourism destination. Popular marine tourism experiences feature scuba diving and dolphin observation, providing guests with the opportunity to witness thriving coral reefs and diverse marine life, thereby aiding in the economic development of the community. With the vast expanse of Indonesian waters and its MPAs dispersed across separate areas requiring efficient monitoring, the use of artificial intelligent (AI), drones, and satellite monitoring can revolutionize the marine conservation plans for Indonesian waters. This cutting-edge technologies facilitates the analysis of vast datasets, optimizing the detection of illegal fishing activities within MPAs (Chassot *et al.,* 2011), monitoring biodiversity in remote or inaccessible locations (Provost *et al.,* 2020), enabling precise identification of species and habitat changes (Zapata-Ramírez *et al.,* 2023), and facilitating the early detection of environmental hazards such as algal blooms or coral bleaching, which supports proactive management interventions (Sabapathy *et al.,* 2023). Alongside embracing technology, encouraging cooperation among local participants, NGOs, and governmental bodies through data-sharing platforms can be pivotal in the effective management of Indonesia's MPAs. The ministry has put in place a system that allows for real-time access to statistics on resource utilization associated with marine and fisheries data, thereby making this information available to everyone at no cost. Furthermore, the ministry is developing an information-sharing platform for MPAs, called the Command Center, which will soon be accessible to the public. This data-sharing platform facilitates innovative co-management strategies, enabling NGOs, local communities, and government agencies to collaboratively tackle challenges such as overfishing and habitat degradation by pooling collective expertise to optimize conservation outcomes (Olenski, 2011).

Implementing quota-based fishery systems

According to the National Commission for Fish Stock Assessment, as detailed in the Ministry of Marine Affairs and Fisheries Regulation No. 19 of 2022 (MMAF, 2022), Indonesia's fish resources are estimated at 12.1 million tons annually, with a TAC of 8.6 million tons per year. The Ministry asserts that sustaining this significant potential relies on proper management, which demands the active participation of all stakeholders and the implementation of robust

regulations and strategies. Several strategies have been implemented, including the establishment of six fish catch zones, the quota-based fishing implementation model in Zone 3, strengthening of vessel licensing and fisheries information systems, enhanced monitoring of fish resources, development of Modern Fishermen's Villages, modernization of fishing ports, improvement of the quality and standards of fish products, enhancement of the downstream fishing industry, and bolstering human resources in the maritime and fisheries sectors. The recent implementation of the catch quota system by MMAF, as it ruled in Government Regulation 11/2023 on measured fishing, also known as Indonesia's quota management, represents a significant effort of the country's fisheries management measure. Following its introduction last year, the system has seen a gradual rollout, with specific vessels receiving assigned quotas. The primary goal of the penangkapan ikan terukur (PIT), or known as Indonesia's quota management program is to boost local economic growth by streamlining the fishing industry—from catching fish at sea, landing them at nearby ports to reduce costs, processing the catch in integrated business zones, and efficiently marketing the processed products both domestically and internationally (MMAF, 2023). Industrial fishing operations within fisheries management area 718 (Arafura and Timor Sea) are no longer required to transport their catch to Java, specifically to Jakarta or Surabaya. Instead, they can land their catch in Sorong, Timika, or Merauke, process it locally, and then sell the high-value processed fish directly to the local markets in Jakarta or Surabaya or export it to international markets. According to projections from the Ministry of Marine Affairs and Fisheries, the introduction of quota-based fishing in Zone 3 is expected to create a multiplier effect of 2,6 Billion USD. This is based on a quota of 1.2 million tons allocated to 3,000 vessels (MMAF, 2023). The detailed multiplier impacts across various categories are outlined in Table 2.

Numerous studies from various countries, particularly those with well-regulated fisheries, have thoroughly documented the advantages of catch quota systems. Investigations into quota-based fishing practices have shown that implementing catch quotas not only benefits the livelihoods of fishers but also stimulates local economies and makes a substantial contribution to the national economy. A study conducted by Cope and Charles (2023) showed that adopting quota-management systems results in socio-economic benefits. The benefits were distributed among vessel owners, skippers, processors, and local traders, eventually supporting the livelihoods of entire communities. Furthermore, the catch quota framework holds the promise of fulfilling various aims in fisheries management, including the promotion of sustainability and the enhancement of economic performance (Hoshino *et al.,* 2022). By stabilizing catch rates and providing economic incentives for sustainable practices, individual transferable quotas (ITQs), one of the most advanced quota mechanisms, have improved livelihoods for commercial and recreational fishers (Arnason, 2012). Another study by Sigler and Lundsford (2001) showed that vessels actively participating in the quota-based system experienced a significant increase in fishing efficiency and substantially reduced immature fish harvested in the Alaska sablefish fishery. Ultimately, this quota generates economic savings and fosters

Table 2: The predicted multiplier effect of quota-based fishing in the Zone 3

Category	Details
Quota	1.2 million tons
Estimated revenue	74,4 million USD
Quota of vessels	3,000 vessels
Employment	~59,150 people employed
Crew members	48,032 crew members
Loading/Unloading jobs	8,556 jobs
Processing unit jobs	2,562 jobs
Shipyards	100 shipyards and docks
Fishing industry	85 fish processing units
Ice Factories	40 ice factories
Clean water	135,090 m^3/month needed
Fuel	450,300 KL/month needed
Total money circulated	2.6 billion USD

better conservation outcomes, thereby collectively improving the livelihoods of fishers. A quota-based management system designed by MMAF is aimed to ensure commercial fish stock health that eventually benefit the economy and the community by limiting the catch. A study by Giron *et al.* (2021) emphasized that effective fisheries management is essential for long-term sustainability, but focusing solely on ecological goals risks overlooking the well-being of fishers. A significant number of fishers taking part in the quota have reported fishing wages that do not meet minimum living standards, even though their fisheries are effectively managed for sustainability. Improving fisher livelihoods requires integrating broader social policies and addressing economic equity alongside ecological management. On the other hand, effective fisheries management, like a quota system, requires accurate data on fish populations, and strict enforcement of the quotas is essential (Narwati and Kumala, 2023). The Indonesian government, through MMAF, has introduced several vital regulations to support the PIT program. The regulation includes Law 31/2004, as amended by Law 45/2009, which serves as the legal foundation for fisheries management. The breakdown of the technical arrangement of the quota is arranged under Government Regulation 11/2023 and Ministry Regulation 28/2023, which provides detailed guidelines for the system's implementation. As a considerable segment of Indonesia's fishing community consists of small-scale operators, it is crucial for these fishers to derive significant benefits from the quota system. The government facilitates support for small-scale fishers by simplifying the process of obtaining fishing licenses and eliminating fees for vessels that are under 5 gross tonnage (GT). The quota system divides the allocation into industrial, local (small-scale fishers), and non-commercial. The industrial quota applies to fishers operating vessels beyond 12 nautical miles offshore, while local fishers are assigned quotas for fishing within 12 nautical miles. Activities such as recreational fishing and research are allocated under the non-commercial quota. Central regulations dictate the particulars of the PIT program, which are further elaborated in ministerial regulations and decisions (Indonesia Government, 2023). The PIT quota system also designates certain fishing zones exclusively for small-scale fishers to reduce competition and minimize conflicts with more extensive industrial operations. Zones 05 and 06 are reserved for local fishers or local investors, either working individually or in cooperative groups, which are typically small-scale. On the other hand, Zones 01 through Zone 04 are intended for local and foreign investors, mainly for vessels with more than 30 GT size and operated over 12 nautical miles from offshores. The objective of this zoning strategy is to preserve fishing resources and foster sustainable practices through the regulation of fishing locations and methods, thereby supporting overarching environmental conservation initiatives. A study by Sulanke and Rybicki (2021) found that a quota system implemented in the Alaska Pollock fishery has helped strengthen local economies by giving small-scale fishers better access to quotas. In the context of Danish fisheries, the implementation of a quota management system has led to greater economic sustainability. It has improved the profitability of the fleet while simultaneously addressing issues of overfishing and excess capacity, thereby fostering a more efficient use of resources that supports the blue economy (Merayo *et al.,* 2018). The environment and local communities are believed to be significantly benefited by the correct implementation of the quota systems guided by solid policies. Indonesia could strengthen its leadership in regional fishery management and drive the growth of its blue economy by accommodating this approach. Equipping local fishing communities with the resources and knowledge needed to embrace sustainable fishing practices—leveraging education, technology, and community-based management strategies that incorporate local ecological knowledge—is crucial for the effective implementation of sustainable fisheries. To bolster these initiatives, the ministry has established a dedicated training and education center, where field extension officers engage directly with fisher groups to disseminate best practices and share successful experiences among both fishers and farmers. This model of community participation has been recognized by. Chen *et al.* (2020), promotes sustainable livelihoods while safeguarding marine ecosystems. Therefore, PIT will protect the country's biodiversity and promote economic growth through the sustainable use of its marine resources.

Development of sustainable aquaculture

Indonesia boasts a vast potential for aquaculture, with an estimated area of 17.91 million hectares,

Table 3: Market values and global market share of five Indonesia' Champion commodities

No	Champion commodities	Market value	Global market share (%)
1	Shrimp	60.4 Billion USD	6.7
2	Seaweed	16.7 Billion USD	16.4
3	Tilapia	13.9 Billion USD	9.7
4	Crab	879 Million USD	1.9
5	Lobster	7.2 Billion USD	0.5

divided into 2.96 million hectares of brackish water, 2.83 million hectares of freshwater, and 12.12 million hectares of seawater (MMAF, 2023). At present, merely 6% of the land that has potential for aquaculture is in use. To tackle this issue, Indonesia has initiated several strategies focused on improving productivity through the revitalization and modeling of aquaculture systems. Key actions include the formation of aquaculture villages, the sourcing of local feed materials, the enhancement of product value and market accessibility, the establishment of Broodstock Centers, and the strengthening of human resources, regulatory frameworks, and oversight mechanisms. Furthermore, there is a concerted effort to enhance the downstream sector, particularly in cold storage and fish processing operations. These strategies target the development of five essential commodities: shrimp, seaweed, tilapia, lobster, and crab based on their global market share values, as shown in Table 3.

Indonesia has enacted several regulations to boost the aquaculture sector's productivity further and maximize the blue economy's economic benefits. This includes Law No. 31/2004 as amended by Law No. 45/2009 on Fisheries, Law No. 7/2016 on the Protection and Empowerment of Fishers, Aquaculturists, and Salt Farmers, Government Regulation No. 28/2017 on Aquaculture, Government Regulation No. 21/2021 on Spatial Planning, and Ministerial Regulation No. 55/2020 from the Ministry of Marine Affairs and Fisheries regarding the procedures, requirements, and designation of aquaculture areas. Designed to facilitate sustainable growth in the aquaculture sector, these regulations ensure that it plays a vital role in the national economy, while also advocating for environmental protection and the development of local communities. One example of implementing sustainable aquaculture development is constructing a 60-hectare Shrimp Aquaculture Area (BUBK) in Kebumen, Central Java. This comprehensive shrimp farming region integrates the upstream and downstream activities of the shrimp pond industry, offering vital assistance to shrimp hatcheries, feed suppliers, shrimp processing operations, ice production facilities, andcold storage facilities. It was noted this farming project has successfully increased the productivity of shrimp farms in Indonesia from 0.6 tons per hectare per cycle to 40 tons per hectare per cycle, boosting the local farmers' economy and expanding local employment opportunities. According to a study by Mori *et al*. (2023), the aquaculture sector in Indonesia has greatly contributed to the local economy, enhancing the livelihoods of communities, especially for farmers who have implemented advanced farming technologies that help decrease operational costs. Aquaculture has also generated employment opportunities beyond farming to include related sectors like feed production, equipment manufacturing, and processing, thereby reducing unemployment in coastal regions. Additionally, the sector has supported gender inclusivity by opening up job opportunities for women, particularly in processing and market sales, thereby enhancing their economic and social roles within the community (Sari *et al.,* 2017). In order to promote sustainable aquaculture and mirror the success of the 60 ha, shrimp farm in Central Java, Indonesia may benefit from the adoption of cutting-edge technologies, the development of solid infrastructure, and the provision of effective policy support. Precision aquaculture techniques, such as automated feeding systems and water quality monitoring, can optimize efficiency and reduce environmental impact, while shared infrastructure like water treatment facilities and renewable energy sources can lower costs for farmers. By fostering capacity building through training and cooperative efforts, best practices are effectively shared, and the combination of streamlined permitting and financial incentives facilitates sustainable development. Certification programs, like best aquaculture practice (BAP) or aquaculture stewardship council (ASC), can

open premium markets, and cluster-based farming systems can address scalability challenges by pooling resources.

Small islands and marine resources surveillance and controlling

The Ministry of Marine Affairs and Fisheries has established a comprehensive surveillance and control platform, the Integrated Maritime Intelligent Platform, or Command Center. This platform allows them to monitor all centrally licensed vessels over 30 GT across Indonesian waters. Data from this platform reveals that the most common fishing violation in 2023 was ship-to-ship transshipment, with 4049 cases recorded in Zone 3 and 2503 cases in Zone 6. Another prevalent violation occurred in coastal operations, where vessels were observed navigating too near to the shore, falling within the banned 7-12 nautical mile area, as depicted in Fig. 3.

The analysis reveals that these regions demand more rigorous monitoring or supplementary resources to guarantee adherence to regulations. However, the fact that these violations are consistently recorded and categorized across all zones denotes the effectiveness of Indonesia's monitoring systems. The challenge now is to translate this to field-level enforcement. Since launching the command center, Indonesia's ability to monitor fishing vessels and respond to regulatory violations has significantly improved. With the Command Center platform, duty officers can oversee vessel movements in real-time using satellite monitoring, which allows for the recording of violations and the commencement of enforcement actions. Field officers then act on instructions from the command center to intercept or address violations at sea. As shown in Figure 3, the trends highlight how much more effective surveillance and enforcement have become, showing that serious actions have been taken to preserve the country's marine resources. The MMAF now

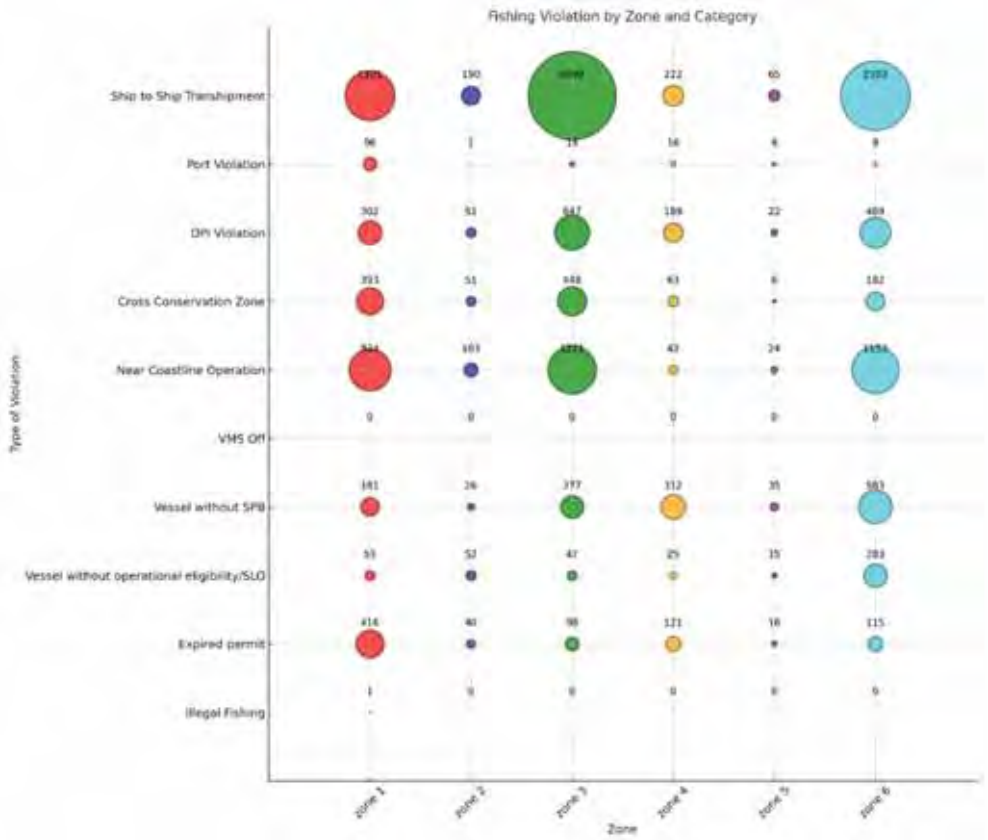


Fig. 3: The type of fishing violation in 2023 monitored and recorded by Command Center Platform (MMAF, 2024)

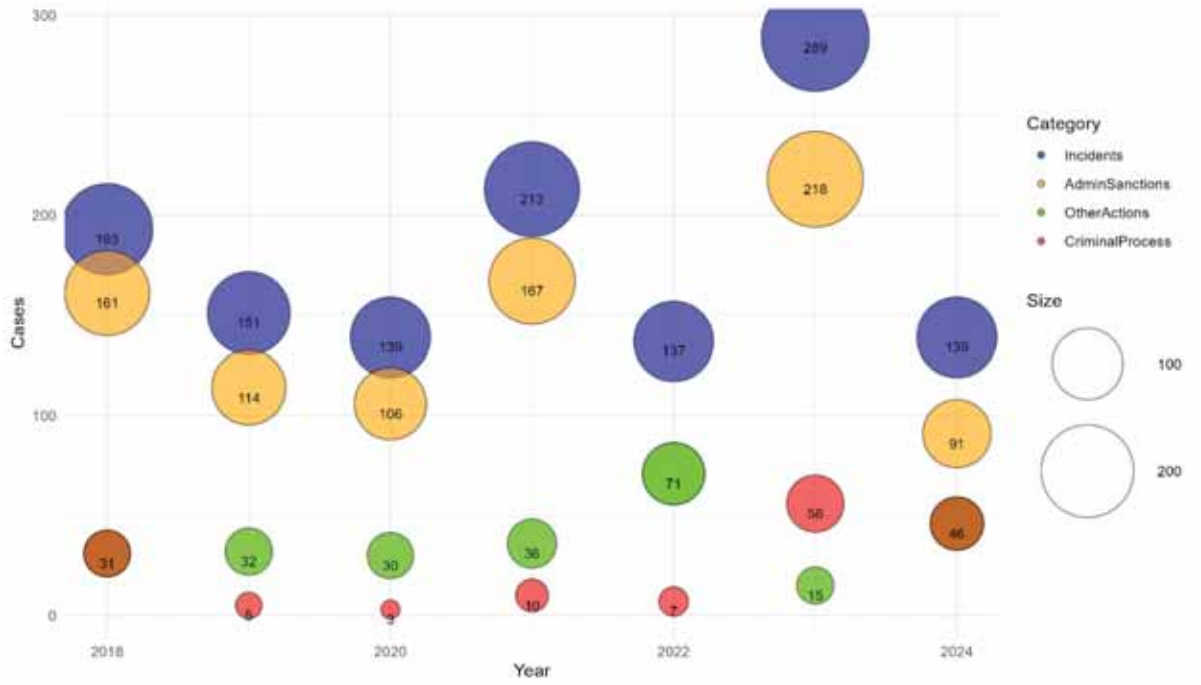


Fig. 4: The number of marine and fisheries violation incidents successfully addressed by the ministry between 2018 and 2024

addresses not only fishing violations but also a wide range of infractions related to the marine and fisheries sector through its Command Center platform. These infractions involve activities including unlawful sea sand mining, unauthorized changes to marine spatial configurations, construction at sea without proper permits, the use of explosives in aquatic environments, electric fishing, holding lobster larvae without a valid trade license, fishing with chemicals, and the transport of protected or endangered fish species without the requisite licenses. Fig. 4 illustrates the total number of violations recorded from 2018 to 2024, as well as the incidents that have been pursued for criminal prosecution or resolved through administrative sanctions. While criminal charges often culminate in jail time, administrative sanctions tend to impose milder consequences, such as fines that are contingent upon the specific violation.

Fig. 4 also shows the effectiveness of the command center since it was set up in 2022. Before that period, while enforcement mechanisms were in place, many incidents were not adequately documented through monitoring and surveillance. The enhanced recording system led to the highest number of documented incidents in 2023, following the establishment of the command center the previous year. This significant increased numbers of violations in 2023 reflects the improved system's ability to address these issues more effectively. From 289 cases documented in 2023, about 75% (218 incidents) were processed to administrative charges, and only 19% (56 cases) were processed as criminal penalties, allowing the Ministry to maximize the income from non-tax revenue. It is believed that utilizing administrative sanctions to handle violations will improve tax revenue from the fisheries sector and act as a more robust deterrent for violators than criminal penalties.

Cleaning up marine plastic waste movement through fishermen participation initiatives

A recent study reported by the World Bank (2021) and the Indonesian MMAF (2023) show that the country produces between 0.2 and 0.55 million tons of plastic waste annually that end up in its waters, with the marine and fisheries sectors producing about 75,300 tons of that waste annually, or 12.7% of all marine plastic waste. Consequently, the MMAF launched the "Month of Loving the Sea," a program designed for fishermen to engage in efforts to eliminate plastic debris from the ocean. Several tactics are used to carry out this campaign, such as setting aside one month per year for fishermen

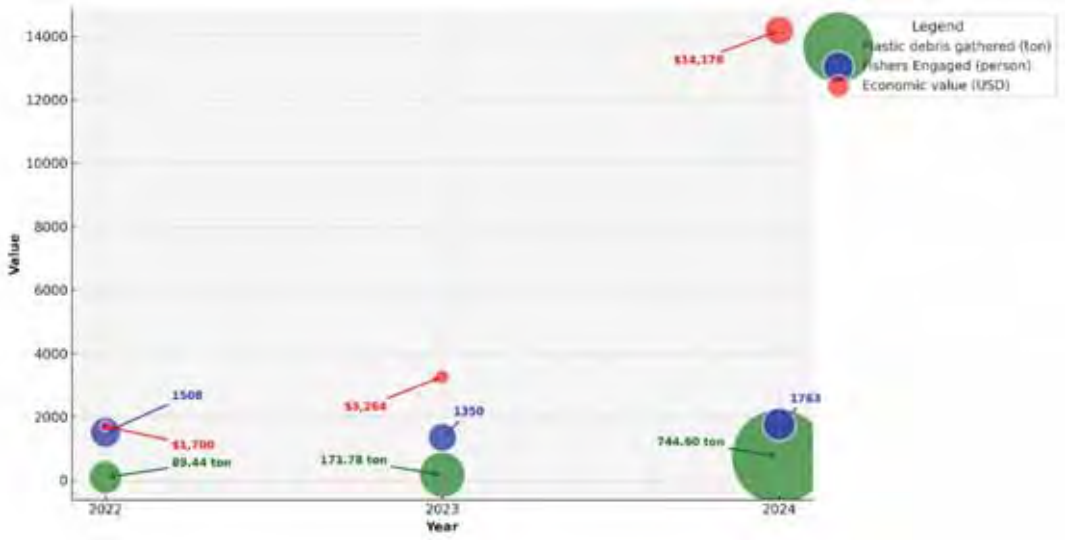


Fig. 5: The value, number of waste gathered, and number of fisher engagement of marine plastic waste clean-up movement initiated by MMAF

to concentrate on gathering and gathering plastic debris from the ocean and coasts. The waste that has been collected is compensated at rates similar to the lowest market prices for fish, with efforts focused on processing the marine waste to generate economic value. The goal of this initiative is to steer Indonesia towards a considerable reduction in marine litter and to create a penta-helix partnership for the management of marine plastic waste, incorporating the government, community, academia, businesses, and the media. Engaging fishers in this clean-up movement not only raises their awareness but also multiplies the reduced number of plastic waste generated mostly by the fishers and fishing activities themselves. Collecting and recycling plastic offers economic gains that can aid in lessening environmental effects and encouraging sustainable practices among coastal communities. According to the MMAF, the national "Month of Loving the Sea" movement, as shown in Fig. 5, was launched at 18 locations across Indonesia in 2023 and expanded to 22 locations in 2024. From this initiative, 89.5 tons of plastic waste were collected in 2022, and this figure nearly doubled to 171.8 tons in 2023. Over two years, 2,858 people have participated in the movement, creating a circular economy at the sites where the initiative was implemented.

The comprehensive review of Indonesia's Blue Economy initiatives reveals significant benefits and challenges across the five critical programs: enhancing marine conservation, implementing a quota-based fishery system, monitoring coastal and small islands, improving aquaculture practices, and initiating a marine plastics cleanup movement. Each initiative offers both economic and environmental benefits to the community, yet they encounter obstacles that necessitate appropriate intervention. For instance, a study by Putra *et al.* (2021) regarding the impact of MPAs in the Anambas waters has shown substantially increased fish diversity, density, and biomass over a four-year study. The study revealed that despite the lack of significant alterations in coral cover, the protective measures were effective in restoring economically significant reef fish species, thereby offering indirect advantages to coral reef ecosystems. In addition, a study by Elliot *et al.* (2001) showed that Wakatobi National Park in Eastern Indonesia has benefited significantly from its protected status and active community involvement. While marine reserves offer considerable benefits, the implementation and management of marine conservation areas in Indonesia encounter significant difficulties. These challenges include legal and regulatory issues, institutional and cultural obstacles, budget constraints, limited human resource support, and failures in participation and communication.

Such challenges obstruct the effective management of resources and require thorough solutions that include solid legal frameworks, involvement from the community, and collaborative management techniques (Suraji *et al.,* 2014; Clifton, 2003; Nugraha, 2021; Tam, 2015; Kusumawati and Huang, 2015; White *et al.,* 2021). A notable case study is the evaluation of the MPA network implementation in fisheries management area (FMA) 715, covering Maluku, West Papua, Tomini Bay, and the Banda Sea. The establishment of this MPA network required a thorough process to ensure successful implementation. White *et al.* (2021) highlight challenges such as the complexity of science and management, multi-jurisdictional implementation, and reliance on external facilitation, while emphasizing the importance of stakeholder education and legal and governance frameworks in MPA network planning. Due to budget limitations and educational hurdles, Indonesia can support its marine conservation initiatives by utilizing blue bonds, green financing, and public-private partnerships. Simultaneously, educational programs can equip local communities with sustainable skills, promote research-based policy formulation, and cultivate a culture of marine conservation through active public involvement. The blue bonds financing could help small island country like Indonesia to raise capital for friendly-ocean project (March *et al.,* 2023), bringing the Indonesia's vast MPA expanded greatly and monitored efficiently. Endarto *et al.* (2025) reported that Indonesia, as a leading archipelagic nation with immense blue economy potential, could adopt the Philippines' approach by implementing a legal framework similar to the Blue Economy Act and Securities and Exchange Commission (SEC) Memorandum Circular No. 15, Series of 2023. This legal framework would lay a solid regulatory groundwork for the issuance of blue bonds, facilitating sustainable marine economic development and reinforcing Indonesia's status as a central maritime hub on the global stage. The private sector can actively contribute to marine conservation projects through public-private partnerships. For instance, the Indonesia Ministry of Finance has established the Indonesia Environment Fund (IEF) to secure funding from facilitators and channel it via a Custodial Bank. These funds are available for private companies to support the execution of eco-friendly initiatives, which may include projects in the marine and fisheries industries (Kurniawan and Kurniawan, 2022). To safeguard and restore marine biodiversity, Indonesia can adopt comprehensive and scalable ecosystem-based management (EBM) techniques. EBM integrates marine spatial planning to harmonize biodiversity conservation with socioeconomic objectives, optimizing resource use while promoting sustainability (Crowder and Norse, 2008). Additionally, Indonesia can enhance species migration and connectivity across its vast MPAs by establishing biological corridors. This can be achieved by advancing marine spatial planning (MSP) using tools like least-cost and circuit theory, where these methodologies have been successfully implemented in the European Union and Canada (Podda and Porporato, 2023). After being temporarily paused in December 2023 to allow for better preparation, the PIT program is back on track, with the Ministry now launching a pilot project. This pilot project includes private fishing firms that are actively participating in a quota-based framework, where quotas are distributed based on the historical catch data of individual vessels. The program also requires that these vessels land their catch at the closest fishing ports to where they operate. All fishermen operating in FMA 718 in the Arafura and Timor Seas must transport their catch to ports located in Dobo or Tual. While the PIT program represents a crucial advancement in the governance of Indonesia's fishing industry, its implications extend beyond mere quota allocation. The objective is to relocate all the fishing processes close to the areas where the fish are caught. This strategy will nurture the local economy, especially in the remote areas of eastern Indonesia, since the fishing, landing, and fish processing are conducted near local ports. It is expected that this strategy encompasses generating employment opportunities, promoting local fishing sectors, and stimulating economic development in these areas. Consequently, it opens up further possibilities for coastal communities across the country. As the quota system continues to evolve, it faces several challenges, notably in the formulation of a clear and effective framework for allocating quotas. The MMAF has ruled several regulations to support the program, including Government Regulation 11/2023, the Minister of Marine Affairs and Fisheries Regulation No. 28/2023 on the Implementation of PIT, and Ministerial Decree

187/2023 that regulated landed fishing port of implementing the quota management system. These regulations are intended to guide and detail the program's implementation. As the quota system continues to evolve, it faces several challenges, notably in the formulation of a clear and effective framework for allocating quotas. Only around 10% of the catch meets the export quality standards demanded by companies in Tual and Dobo, compounded by the limited capacity of the processing plants. In the event that the catch is left and does not conform to these standards, it must be transported back to Java, where it can be utilized by local markets. From a business perspective, vessel owners find it difficult to land their catch at these nearby ports because it isn't profitable, leading to lower sales and financial strain. Several challenges have emerged in the implementation of quota-based fishing, such as issues related to regulation and enforcement, opposition from stakeholders, and the socio-economic repercussions for local fishing communities. For example, fishers (including the boat owners and skippers) often resist quota policies due to perceived unfairness and lack of involvement in decision-making. However, this situation can be overcome by better communication and collaboration between the government and stakeholders (Narwati and Kumala, 2023). Alternatively, there is a need for clearer policies that distinguish between small, medium, and large-scale fishing vessels. Such clarity is crucial to allow small-scale sectors to be exempt from local quotas that apply outside national jurisdiction, or when such quotas are unsuitable for their operational scale. Several practical solutions could be implemented to address these challenges. Firstly, launching more fish processing near the landing ports in eastern Indonesia will allow more catch to meet export standards and reduce the possibility of the catch being transported back to Java. Secondly, enhance the regulatory framework such as clear regulation and penalty system as well as transparent quota allocation system will ensure compliance among stakeholders. Thirdly, to improve the community engagement, the government can involve fishers, cooperatives, and local government in quota planning and decision-making to ensure buy-in, and Ensure smaller-scale fishers have access to quotas, preventing monopolization by large commercial operators. It is expected that the business process will boost the revenue of the local fishers and stimulate job creation and economic growth within these regions. Moreover, implementing financial incentives or subsidies for vessel owners who deliver their catch to these ports could mitigate the effects of diminished profits and foster compliance with the PIT program. Therefore, the PIT system establishes measurable and controlled fishing quotas to prevent overfishing and ensure resource sustainability while the modern infrastructure such as well-equipped ports and modern cold storage facilities creates efficient logistics and processing systems that reduce post-harvest losses, ensuring that the fish caught under PIT guidelines are utilized effectively, thereby enhancing profitability. A significant number of interviewees pointed out that the effectiveness of quota-based management programs is largely influenced by a lack of transparency, collaboration, and clearly defined responsibilities among the government, local communities, and private sector entities. To overcome these challenges, it is essential to promote greater accountability, openness, and collaboration among stakeholders. For instance, obtaining quotas through fishers' cooperatives should be straightforward and accessible for individuals licensed by either provincial or central authorities, and these should be administrable by the ministry. Study conducted by Satria and Matsuda (2004) highlighted that decentralizing fisheries management fosters local ownership and participatory governance, empowering traditional community-based systems to co-manage resources effectively and address quota-related challenges in partnership with government authorities. Ongoing scientific evaluations can establish flexible quotas, whereas spatial zoning and designated no-take zones promote the sustainable utilization of resources. Advanced technologies, such as real-time monitoring and vessel tracking, improve compliance and help curb illegal fishing. Concurrently, economic incentives, such as subsidies aimed at promoting sustainable practices and certifications for green products, improve financial outcomes. Involving fishers through educational initiatives and alternative income streams, including aquaculture and eco-tourism, helps to lessen the demand on wild fish stocks. By monitoring outcomes and adopting adaptive management, Indonesia can guarantee lasting sustainability and economic potential of its fisheries sector. At the end, the country can optimize

its quota-based fishing system by integrating scientific stock assessments conducted by National Stock Assessment Committee, utilizing advanced technology, and improve stakeholder collaboration to balance fish stock protection with economic growth. The extensive information gathered from several fishing violation cases in 2023 highlights the occurrence and spread of violations throughout six designated zones. High occurrences of violations like "Ship to Ship Transshipment" and "Near Coastline Operation" in zones 3 and 6 highlight areas needing more stringent monitoring. The regular tracking and organization of violations in every zone illustrate the success of Indonesia's monitoring systems. Since the establishment of the Command Center, it has been noted that the platform has dramatically enhanced the surveillance ability to comprehensively record, monitor, and address fishing vessel violations; improving surveillance and enforcement mechanisms target is essential for combating illegal fishing activities. The new monitoring platform, the Integrated Maritime Intelligent Platform, can be enhanced by incorporating advanced technologies to improve the detection of marine violations and increase fine revenue. Currently, the vessel monitoring technology implemented through the Command Center platform has empowered AI-based analytics and machine learning to detect patterns and anticipate high-risk areas for violations, such as transshipments between ships and activities close to the coastline. Integrating automated alerts for prohibited activities, like unauthorized vessel movements within restricted zones, can enable faster responses on the filed or ground level and reduce operational cost. Additionally, deploying drones and autonomous underwater vehicles (AUVs) for close-range monitoring and evidence collection can complement satellite tracking, providing comprehensive surveillance. Enhancing data-sharing capabilities with local authorities and fostering collaboration across agencies can optimize enforcement efforts and better allocate resources to areas identified as high-risk. On the other hand, the Marine Plastics Cleanup Movement has significantly reduced marine plastic pollution, removing nearly 200 tons of marine debris within just two years and supporting the local circular economy. To further involve the public, the MMAF has raised community awareness through prominent social media and prominent influencers regarding the harmful effects of plastic waste. As a commitment, the MMAF has introduced a Ministerial Decree focused on reducing marine plastic litter, particularly from fishing activities primarily generated from fishing ports. Interviews and reports from major fishing ports throughout the country indicate that the ongoing challenge of marine plastic pollution is primarily due to inadequate waste management systems, limited awareness, and ineffective collaboration among stakeholders. Raising public awareness and boosting community engagement are vital hurdles the government faces in reducing marine plastic waste. The country can innovate tools to accelerate efforts to eliminate marine plastic pollution. Community-driven approaches, such as the decision cycle for development (DeCyDe-4) method, a decision-making framework designed to reduce marine plastic pollution (Loizidou *et al.,* 2020) and digital tracking of marine waste (Pestana *et al.,* 2023), can help the development of context-specific policies and solutions to combat marine litter. Both of these tools have demonstrated their ability promoting the integration of circular economy principles (Pestana *et al.,* 2023). The introduction of environmentally friendly packaging options could lead to a substantial decrease in plastic food packaging, which is often a significant contributor to ocean debris. At present, the ministry is promoting the use of reusable drink bottles (tumblers) among all staff, especially those stationed at fishing ports. However, this initiative should be widely amplified through social media campaigns to ensure broader reach and impact. Although the MMAF faces significant challenges with the five key initiatives, the Ministry has developed an advanced information system to address these issues effectively. The Ministry is harnessing technological advancements to greatly enhance the implementation of its priority initiatives. For instance, it is currently developing the Integrated Maritime Intelligent Platform or Command Center that uses advanced algorithms to monitor fishing vessel movements across all Indonesian waters. This platform integrates information from the vessel monitoring system (VMS), communication satellites, capture fisheries production statistics, and data from nano-satellites. The system processes this information to display real-time movements of fishing vessels along with their technical details, such as permit validity, type, size, ID,

owner, and company name, on a dashboard, simplifying monitoring and surveillance efforts. An additional form of support involves the implementation of the Ocean Accounting System, a holistic management tool designed for spatial and non-spatial data. This system delivers critical information regarding the value of the country's marine resources and monitors the fluctuations in their balance (credits and debits) over time, influenced by economic activities. This system gathers data on the area and condition of marine ecosystems at two different times (T0 and T1), the extent of national coral reef areas, seagrass ecosystem information, and mangrove areas. The output is information on the balance changes between T0 and T1 in the form of ecosystem asset credits and debits. An unfavorable balance points to the overexploitation or detrimental use of resources, in contrast to a favorable balance, which denotes responsible and sustainable resource management. The development of the Command Center, also called the Integrated Maritime Intelligent Platform, is aimed to address challenges in its five critical priority programs. This system consolidates previously developed platforms within the Ministry into a single platform including integrates real-time vessel tracking, displaying detailed data and information on thousands of industrial-scale fishing vessels operating in Indonesian waters. This platform also includes spatial data for every MPAs and utilizes an advanced algorithm to issue real-time alerts regarding violations, such as illegal fishing practices within these protected zones. Additionally, it notifies duty officers of other violations, including expired fishing licenses, vessels operating too close to the coastline, and transshipment incidents. Consolidating all relevant information from the ministry into a unified Command Center platform represents an innovative solution designed to tackle the complex challenges in Indonesia's marine and fisheries sector, enhancing the implementation of the five key blue economy initiatives. In light of the assessment of five key initiatives and the analysis of the benefits and drawbacks associated with Indonesia's Fisheries Blue Economy, it is vital to establish key measures. This entails enhancing the laws and policies that advocate for sustainable fishing, aquaculture, and the preservation of marine ecosystems. Expanding the MPAs are paramount, but ensuring that they're effectively enforced is another crucial step to preserve our rich biodiversity and keep our fish populations thriving: a) Use advanced monitoring technologies to enhance the enforcement of quota-based fishing systems and prevent overfishing, b) Invest in cutting-edge technologies like the Integrated Maritime Intelligent Infrastructure Sys-tem for better resource management and decision-making, c) Initiate economic incentives for conservation efforts, support community engagement in marine resource management by providing better educational programs and capacity building, and encourage public-private partnerships to leverage resources and expertise, d) Integrate comprehensive waste management strategies to reduce marine debris, mainly plastic waste, e) The Ocean Accounting System is now fully operational, designed to evaluate the economic worth of marine resources and promote their sustainable management. To tackle the issues related to climate change, the country should implement forward-thinking adaptation strategies that merge technology, teamwork, and conservation practices. Implementing an adaptive fisheries management framework supported by real-time monitoring through a centralized Command Center platform can enable precise, data-driven decision-making. Enhanced stakeholder collaboration that fosters knowledge sharing and develops locally tailored solutions can further strengthen these efforts. Moreover, broadening the scope of effective MPAs to preserve essential habitats and biodiversity will enhance the resilience of ecosystems. A successful example is the Philippines' ecosystem-based fisheries management approach, which integrates real-time monitoring systems like FishR, fosters community collaboration to regulate fishing practices, and establishes MPAs such as the Tubbataha Reefs Natural Park to protect ecosystems and biodiversity (Pomeroy *et al.,* 2016; Weeks *et al.,* 2010). Such cohesive approaches create a solid structure for reducing the impacts of climate change while ensuring the sustainable management of marine resources. The country can also incorporate renewable energy technologies, such as tidal energy and offshore wind farms, to deliver clean and dependable energy while safeguarding marine ecosystems. Tidal energy development in regions like the Bali Strait holds significant potential to address energy shortages in certain parts of the country (Dirgantara, 2011), while

a study conducted by Franika *et al.* (2023) showed promising offshore wind turbine in the Java Sea that able to produce green energy while promoting economic growth through job creation and energy sufficiency. Evaluating the long-term environmental and economic impacts of Indonesia's Ministry of Marine Affairs and Fisheries' blue economy programs requires clear and measurable indicators, supported by robust data. Significant environmental metrics could involve the size of MPAs, the decline in fishing violations, biodiversity assessments, water quality standards, and the carbon capture potential of coral reefs and mangrove habitats. On the economic side, indicators might include improvements in the livelihoods of fishers and aquaculture farmers, the quantity of marine plastic removed, and its contribution to the circular economy. These metrics can function as alternatives for gauging future economic performance and the comprehensive success of blue economy efforts. It is the strong conviction that the execution of these strategies will not only advance the sustainability of Indonesia's marine sectors but also establish an international standard for sustainable management of marine resources.

CONCLUSION

Indonesia's Fisheries Blue Economy initiatives demonstrate a strategic commitment to harmonizing ecological preservation with economic advancement. By implementing five key programs—marine conservation, quota-based fisheries, coastal monitoring, aquaculture enhancement, and marine plastic cleanup—the MMAF is effectively addressing the multifaceted challenges associated with sustainable management of marine resources. These programs have already shown tangible benefits, such as increased fish diversity in MPAs and the reduction of marine debris through cleanup initiativesNevertheless, their achievement is contingent upon addressing substantial obstacles, such as regulatory, logistical, and socio-economic challenges. The implementation of advanced technologies, such as the Integrated Maritime Intelligent Platform, has significantly strengthened the MMAF's capacity to monitor and enforce sustainable practices. Real-time vessel tracking, violation alerts, and spatial data integration provide critical tools for addressing illegal fishing and other violations. Furthermore, the Ocean Accounting System establishes a strong foundation for measuring the economic and ecological significance of marine resources, ensuring that decision-making is based on data and supports sustainability objectives. These innovations position Indonesia as a global leader in leveraging technology for marine conservation and resource management. Despite progress, challenges persist, particularly in implementing the quota-based fishing system. Challenges like logistical limitations, restricted processing capabilities, and opposition from stakeholders underscore the necessity for well-rounded strategies. Establishing more processing facilities in eastern Indonesia and offering financial incentives to vessel owners can enhance compliance and economic viability. Enhancing communication and collaboration with local communities is crucial for addressing socio-economic effects and ensuring fair involvement in decision-making processes. To secure the long-term success of these initiatives, Indonesia must continue strengthening its legal frameworks, expanding MPAs with effective enforcement, and integrating waste management solutions to tackle marine pollution. By promoting public-private partnerships, community engagement, and education programs, the MMAF can further its goals of sustainable resource use. By implementing these initiatives, Indonesia has the potential to protect its diverse marine ecosystems while establishing a global standard for sustainable marine governance.

AUTHOR CONTRIBUTIONS

S.W. Trenggono contributed to the conceptualization, manuscript drafting, and editing. I. Meilano provided supervision and reviewed the manuscript draft. H. Latief offered supervision and conducted a relevant literature review. S.D. Diantara supplied the data and assisted with the literature review. W.I. Sakti contributed to drafting the manuscript. D.G.K. Ketaren assisted with data checking and reviewed the references. I. N.P. Winata supported manuscript editing and curation. T. Yuwono contributed to data analysis and prepared the literature review. Syamdidi conducted data interpretation and the literature review. F.Y. Arthatiani assisted with data collection and interpretation. K. Kasim was involved in manuscript preparation, data analysis, and interpretation. I.N. Radiarta performed in the literature review and conceptualization. All authors have reviewed and

approved the final version of the manuscript for publication.

ACKNOWLEDGEMENT

Authors would like to express our sincere appreciation to the Directorate General of Capture Fisheries of MMAF for their valuable insights into the implementation of the Penangkapan Ikan Terukur program and to the Agency for Extension and Human Resource Development of Marine and Fisheries for their support in field data collection. Gratitude also extends to the Directorate General of Marine Spatial Management for sharing key lessons on marine conservation and to the Directorate General of Marine and Fisheries Resources Surveillance for their contributions regarding field implementation experiences.

CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit:

http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims with regard to published maps and institutional affiliations.

ABBREVIATIONS

%	Percent
AI	Artificial intelligent
AUVs	Autonomous underwater vehicles
ASC	Aquaculture Stewardship Council
BAP	Best aquaculture practice
BLUD	Badan Layanan Umum Daerah/ Regional Public Service Agency
BUBK	Budidaya Udang Berbasis Kawasan/ Area-based shrimp farming
DeCyDe-4	Decision cycle for development
EBM	Ecosystem Based Management
FGD	Focus group discussion
Fig.	Figure
FMA	Fisheries Management Area
GT	Gross tonnage
ha	Hectare
ID	Identification
IMO	International Maritime Organization
ITQs	Individual transferable quotas
IEF	Indonesia Environment Fund
KL	Kiloliter
MMAF	Ministry of marine affairs and fisheries
MPA	Marine protected area
MSP	Marine spatial planning
m^3	Cubic meter
NGO	Non-government organization
No.	Number
PIT	Penangkapan Ikan Terukur
SEC	Securities and Exchange Commission
SLO	*Surat laik operasional* (Operational eligibility license)
T0	First time observation
T1	Second time observation
TAC	Total allowable catch
tCO2eq	Ton of carbon dioxide equivalent
USD	United States Dollar
VMS	Vessel monitoring system

REFERENCES

Chassot, E.; Bonhommeau, S.; Reygondeau, G.; Nieto, K.; Polovina, J.; Huret, M.; Dulvy, N.; and Demarcq, H., (2011). Satellite remote sensing for an ecosystem approach to fisheries management. ICES J. Mar. Sci., 68(3): 651-666 (**16 pages**)

Chen, J.; Hsu, K.; and Chuang, C., (2020). How do fishery resources enhance the development of coastal fishing communities: Lessons learned from a community-based sea farming project in Taiwan. Ocean Coastal Manage., 184.

Clifton J., (2003). Prospects for co-management in Indonesia's marine protected areas. Mar. Policy. 27(5): 389-395 **(7 pages).**

Copes, P.; Charles, A., (2004). Socioeconomics of individual transferable quotas and community-based fishery management. Agric. Resour. Ecol. Rev., 33(2).

Costello, M.J., (2024). Evidence of economic benefits from marine protected areas. Sci. Mar., 88(1).

Crowder, L.; and Norse, E., (2008). Essential ecological insights for marine ecosystem-based management and marine spatial planning. Mar. Policy. 32(5): 772–778 (**7 pages)**

Cusack, C.; Suresh, A.S.; Rice, A.N.; Warren, J.D.; Fujita, R.; Ingles, J.; Flores, J.; Garchitorena, E.; S.V. Mesa, (2021). Marine ecotourism for small pelagics as a source of alternative income generating activities to fisheries in a tropical community. Biol. Conserv., 261.

Dirgantara, T.A.T., (2011). Study of fatigue design on marine current turbine support structure Bali – Indonesia. Master Thesis. TU Delf.

Dirhamsyah. (2005). Maritime law enforcement and compliance in Indonesia: problems and recommendations. Mar. Stud., 144: 1-16 **(16 pages).** Australian Association for Maritime Affairs.

Elliott, G.; Mitchell, B.; Wiltshire, B.; Manan, I.; Wismer, S., (2021). Community participation in marine protected area management: Wakatobi National Park, Sulawesi, Indonesia. Coastal Manage., 29(4): 295-316 **(22 pages).**

Endarto, B.; Elok.I.D.; Mardiana, F., (2024). Legal transplantation of blue bond regulation in Indonesia. Environ. Dev., 53.

Franika, R.V.; Ridwan, M.; and Perdana, A., (2023). Analisis teknis dan ekonomi dalam pemanfaatan area sekitar anjungan lepas pantai di laut jawa untuk memproduksi listrik hijau dengan turbin angin lepas pantai. J. Ilmiah Universitas Batanghari Jambi. 23(3).

Giron-Nava, A.; Vicky, W.Y.L.; Octavio, A.O.; William, W.L.; Cheung; Benjamin, S.H.; Rashid Sumaila; U.; Andrés, M.; Cisneros, M., (2021). Sustainable fisheries are essential but not enough to ensure well-being for the world's fishers. Fish. Fish., 22(4): 1-10 **(10 pages).**

Indonesia Government, (2023). Government regulation of the republic of Indonesia number 11 of 2023 concerning measured fishing. Jakarta, Indonesia. 1-29 **(29 pages).**

Green, A.L.; Fernandes, L.; Almany, G.; Abesamis, R.; McLeod, E.; Aliño, P.; Alan, T.W., Rod Salm; John Tanzer; Robert L.P., (2014). Designing marine reserves for fisheries management, biodiversity conservation, and climate change adaptation. Coastal Manage., 42(2): 143–159 **(17 pages).**

Hastuty, R.; Adrianto, L.; Yonvitner, (2015). Kajian manfaat kawasan konservasi bagi perikanan yang berkelanjutan di Pesisir Timur Pulau Weh. J. Teknologi Perikanan dan Kelautan. 6(1): 105-116 **(12 pages).**

Henriksson, P.J.G.; Tran, N.; Mohan, C.V.M.; Chan, C.Y.C.; Rodriguez, U.P.; Suri, S.; Mateos, L.D.; Utomo, N.B.P.; Hall, S.; Phillips, M.J., (2017). Indonesian aquaculture futures – Evaluating environmental and socioeconomic potentials and limitations. J. Cleaner Product., 162: 1482-1490 **(9 pages).**

Hoshino, E.; van Putten, I.; Pascoe, S.; and Vieira, S., (2020). Individual transferable quotas in achieving multiple objectives of fisheries management. Mar. Policy. 113.

Khairunnisa, F., (2022). Blue economic concept on protecting marine ecosystem in Indonesia and China. The Lawpreneurship. 5(2): 34-45 **(12 pages).**

Klein, E.; Watters, G., (2020). What's the catch? profiling the benefits and costs associated with marine protected areas and displaced fishing in the scotia sea. PLoS ONE. 15(8).

Kobayashi, M., (2023). Promoting sustainable fisheries and aquaculture in Indonesia. IOP Conference Series: Earth Environ. Sci., 755.

Kurniawan, R.; Kurniawan, I., (2022). Developing innovative financing scheme for leveraging energy efficiency deployment in Indonesia. Indones. J. Energy. 5(1): 33-41 (**9 pages**)

Kusumawati I.; and Hsiang-Wen Huang, (2015). Key factors for successful management of marine protected areas: a comparison of stakeholders' perception of two MPAs in Weh Island, sabang, aceh, Indonesia. Mar. Policy. 51. 465-475 **(11 pages)**.

LaRue, M.; Brooks, C.; Wege, M.; Salas, L.; Gardiner, N., (2022). High-resolution satellite imagery meets the challenge of monitoring remote marine protected areas in the Antarctic and beyond. Conserv. Lett., 15.

Loizidou, X.; Orthodoxou, D.; Loizides, M.; and Krestenitis, Y., (2020). A community-based approach for site-specific policies and solutions on marine litter: The example of Paphos, Cyprus. Environ. Syst. Dec., 41(1): 33–44 (**12 pages**)

Nneamaka, O.; Chisom, P.; Biu, P.W.; Umoh, A.A.; Obaedo, B.O.; Adegbite, A.O.; Abatan, A., (2024). Reviewing the role of AI in environmental monitoring and conservation: A data-driven revolution for our planet. World J. Adv. Res. Rev., 21: 161-171 (**11 pages**)

Nursey-Bray, M.; Wootton, N.; Holland, S.; Page, K.; Gillanders, B.M., (2024). Site unseen: engaging communities on marine protected areas. Biol. Conserv., 292.

Merayo, E.; Nielsen, R.; Hoff, A.; Nielsen, M., (2018). Are individual transferable quotas an adequate solution to overfishing and overcapacity? Evidence from Danish fisheries. Marine Policy. 87: 167-176 (**10 pages**).

MMAF, (2022). Decree of the minister of maritime affairs and fisheries of the republic of indonesia number 19 of 2022 concerning estimation of fishery resource potential, allowable fish catch, and utilization level of fishery resources in the fishery management areas of the republic of indonesia. Ministry of Marine Affairs and Fisheries. Jakarta, Indonesia.

MMAF, (2023). Roadmap for the blue economy towards golden Indonesia 2045. Ministry of Marine Affairs and Fisheries. PT

Kompas Media Nusantara.
MMAF, (2024). Integrated maritime intelligent platform 2024. Ministry of Marine Affairs and Fisheries.
MMAF, (2024). The statistic report 2024. Ministry of Marine Affairs and Fisheries of Republic of Indonesia.
Mori, L.; Goto, G.; van Dijken S.; Klinger, D., (2023). Realizing aquaculture's blue economy potential in the pacific island region – enabling conditions, barriers and next steps. Food and Agricultural Organization.
Narwati, E.; Kumala, M.T., (2023). Determination of fishing rights allocation as a strategy for sustainable fisheries management realisation in Indonesia. World Journal of Entrepreneurship, Manage. Sustainable Dev., 19(1-2): 27-38 **(12 pages).**
Nugraha, A., (2021). Legal analysis of current Indonesia's marine protected areas development. Sriwijaya Law Review. 5(1): 14-28 **(15 pages).**
Olenski, J., (2011). Statistical parainformation platform - foundation of information transparency in heterogeneous international environment (with special reference to the Eastern Partnership initiative). Statistics Transition New Series. 12: 493-510 (**18 pages**)
Pascoe, S.; Hoshino, E.; Hutton, T.; Hobday, A.J., (2022). Conflicting perceptions of quota-based systems in Australian fisheries. Mar. Freshwater Res., 73: 419-427 (9 pages).
Podda, C.; Porporato, E., (2023). Marine spatial planning for connectivity and conservation through ecological corridors between marine protected areas and other effective area-based conservation measures. Front. Mar. Sci., 10.
Pomeroy, R.; Parks, J.; Courtney, C.; Mattich, L., (2016). Improving marine fisheries management in southeast asia: results of a regional fisheries stakeholder analysis. Mar. Policy. 65(2):20-29 (**10 pages**)
Provost, E.J.; Butcher, P.; Coleman, M.; Bloom, D.; Kelaher, B., (2020). Aerial drone technology can assist compliance of trap fisheries. Fish. Manage. Ecol. 27(5): 381-388 (8 **pages)**
Puspitasari, D.; Chasanah, A.; and Wardhani, M.F., (2023). Strategi peningkatan ketahanan ekonomi untuk perikanan berkelanjutan berbasis konsep blue economy. Value: J. Manajemen dan Akuntansi. 13(1): 25-34 **(10 pages).**
Putra, R.D.; Siringiringo, R.M.; Suryanti, A.; Sari, N; Sinaga, W.P.; Hidayati N.V.; Hukom, F.D.; Abrar, M.; Makatipu, P.C.; Sianturi, R.; and Ilham, Y., (2021). Impact of marine protected areas on economically important coral reef fish communities: An evaluation of the biological monitoring of coral reef fish in anambas Islands, Indonesia. Biodivers. J. Biol. Divers., 22(10): 4169-4181 **(13 pages).**
Sabapathy, C.; Rajesh, S.; Raman, R.; Meenakshi, R.; Parikh, S.; Muthulekshmi, M., (2023). IoT applications in marine monitoring: Protecting ocean health and biodiversity. 2023 International Conference on Sustainable Communication Networks and Application. 305-310 (**6 pages**)
Sari, D.A.A.; Muslimah, S., (2020). Blue economy policy for sustainable fisheries in Indonesia. IOP Conference Series: Earth Environ. Sci., 423.
Satria, A.; Matsuda, Y., (2004). Decentralization of fisheries management in Indonesia. Mar. Policy. 28(6): 437–450 (**14 pages**)
Sen, S., (2010). Developing a framework for displaced fishing effort programs in marine protected areas. Mar. Policy. 34(60): 1171-1177 **(7 pages).**
Sigler, M.; Lunsford, C., (2001). Effects of individual quotas on catching efficiency and spawning potential in the alaska sablefish fishery. Can. J. Fish. Aquat. Sci., 58(7): 1300-1313 **(14 pages).**
Sulanke, E.; Rybicki, S., (2021). Community development quotas and support of small-scale fisheries as two key concepts for blue growth in fisheries. Front. Mar. Sci., 8.
Suraji, T.; Ruchimat, S.; Saad, S.; Wibisana, S., (2014). New paradigm of co-management of MPAs in Indonesia, lessons learned from COREMAP. Transylvanian Rev. Syst. Ecol. Res., 16(2): 181-188 **(8 pages).**
Tam, C.-L., (2015). Timing exclusion and communicating time: A spatial analysis of participation failure in an Indonesian MPA. Mar. Policy. 54(C): 122-129 **(8 pages).**
Trenggono, S.W., (2023). A quota based fishing for the sustainability of Indonesia fishery. J. Kelautan dan Perikanan Terapan Special Edition. 1-8 **(8 pages).**
Sari, I.; McDougall; Cynthia; Rajaratnam, S., (2017). Women's empowerment in aquaculture: Two case studies from Indonesia. the Food and Agriculture Organization of the United Nations and the International Center for Living Aquatic Resources Management. 1-114 **(114 pages).**
White, A.; Rudyanto; Agung, M.F.; Noorafebrianie, M.; Asri, L.; Wen, W'; Yusuf, F.; Alison, G.; Stacey, T., (2021). Marine Protected Area Networks in Indonesia: Progress, Lessons and a Network Design Case Study Covering Six Eastern Provinces. Coast. Manage., 49: 575-597 **(23 pages).**
World Bank, (2021). Oceans for prosperity: reforms for a blue economy in Indonesia. The World Bank. Washington, D.C 2021.
World Bank, (2021). Plastic waste discharges from rivers and coastlines in Indonesia. Marine Plastics Series, East Asia and Pacific Region 2021. Washington DC.
World Bank, (2023). Making Waves: World Bank support for the blue economy. Independent Evaluation Group. Washington, DC: 2012–23 **(12 pages).**
Zapata-Ramírez, P.; Hernández-Hamón, H.; Fitzsimmons, C.; Cano, M.; García, J.; Zuluaga, C.; Vásquez, R., (2023). Development of a google earth engine-based application for the management of shallow coral reefs using drone imagery. Remote Sens., 15(14): 3504
Ziegler, S.L.; Brooks, R.O.; Bellquist, L.F.; Caselle, J E.; Morgan, S.G.; Mulligan, T.J.; Ruttenberg, B.I.; Semmens, B.X.; Starr, R.M.; Tyburczy, J.; Wendt, D.E.; Buchheister, A.; Jarrin, J.R.M.; Pasparakis, C.; Jorgensen, S.J.; Chiu, J.A.; Colby, J.; Coscino, C.L.; Davis, L.; de Castr, F.; Elstne, J.T.; Honeyman, C.; Erica, T.J.M.; Erin, M.J.; Sadie L.S.; Staton, J.; Waltz, G.T.; Basnett, B.; Satterthwaite, E.V.; Killeen, H.; Dibble, C.D.; Hamilton, S.L., (2024). Collaborative fisheries research reveals reserve size and age determine efficacy across a network of marine protected areas. Conserv. Lett., 17.

AUTHOR (S) BIOSKETCHES

Trenggono, S.W., Ph.D. Candidate, Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology. Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat, Indonesia. Ministry of Marine Affairs and Fisheries – Gedung Mina Bahari 1, 7th Floor, Jl. Merdeka Timur, Gambir, Jakarta Pusat, Indonesia
- Email: *sakti_trenggono@yahoo.com*
- ORCID: 0009-0005-2706-6194
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/fakultas-ilmu-dan-teknologi-kebumian

Meilano, I., Ph.D., Professor, Dean Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat, Indonesia.
- Email: meilanoirwan@gmail.com
- ORCID: 0000-0003-3488-9154
- Web of Science ResearcherID: NA
- Scopus Author ID: 12808186900
- Homepage: https://fitb.itb.ac.id/irwan-meilano/

Latief, H., Ph.D., Instructor, Physical Oceanography, Bandung Institute of Technology, Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat, Indonesia.
- Email: *hamzah@fitb.ac.id*
- ORCID: 0009-0002-9250-0004
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/staf/profil/hamzah-latief

Diantara, S.D., Ph.D. Candidate, Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology. Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat, Indonesia. Ministry of Defense, Jl. Budi Kemulyaan No 4-6, Jakarta Pusat, Indonesia.
- Email: *supo.dwi@yahoo.com*
- ORCID: 0009-0006-2033-0762
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/fakultas-ilmu-dan-teknologi-kebumian

Sakti, W.I., Ph.D., Instructor, Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology. Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat. Universitas Tarumanegara, Jl. Letjen S. Parman No. 1, Grogol Petamburan, Jakarta Barat, DKI Jakarta, Indonesia.
- Email: *wahyu_saidi@yahoo.com*
- ORCID: 0009-0007-0307-6253
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/fakultas-ilmu-dan-teknologi-kebumian

Ketaren, **D.G.K.,** Ph.D. Candidate, Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology. Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat. Indonesia.
- Email: *ketaren_david@yahoo.com*
- ORCID: 0009-0004-2940-1702
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/fakultas-ilmu-dan-teknologi-kebumian

Winata, I.N.P., Ph.D. Candidate, Oceanography, Bandung Institute of Technology, Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat, Indonesia. Ministry of Marine Affairs and Fisheries – Gedung Mina Bahari 1, 7th Floor, Jl. Merdeka Timur, Gambir, Jakarta Pusat, Indonesia
- Email: *p.nengah42@yahoo.com*
- ORCID: 0009-0008-9307-0783
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/fakultas-ilmu-dan-teknologi-kebumian

Yuwono, T., Ph.D. Candidate, Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology. Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat. [2]Ministry of Marine Affairs and Fisheries – Gedung Mina Bahari 3, 7th Floor, Jl. Merdeka Timur, Gambir, Jakarta Pusat, Indonesia.
- Email: *triyu.mail@gmail.com*
- ORCID: 0009-0005-3362-7373
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/fakultas-ilmu-dan-teknologi-kebumian

AUTHOR (S) BIOSKETCHES

Syamdidi, Ph.D. Candidate, Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology. Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat, Indonesia. Ministry of Marine Affairs and Fisheries – Gedung Mina Bahari 3, 7th Floor, Jl. Merdeka Timur, Gambir, Jakarta Pusat, Indonesia.
- Email: *syamdidi@gmail.com*
- ORCID: 0000-0001-9172-2428
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/fakultas-ilmu-dan-teknologi-kebumian

Arthatiani, F.Y., Ph.D. Candidate, Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology. Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat, Indonesia. Ministry of Marine Affairs and Fisheries – Gedung Mina Bahari 3, 7th Floor, Jl. Merdeka Timur, Gambir, Jakarta Pusat – Indonesia.
- Email: *ketaren_david@yahoo.com*
- ORCID: 0009-0005-0518-2127
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://itb.ac.id/fakultas-ilmu-dan-teknologi-kebumian

Kasim, K., Ph.D. Candidate, Oceanography and Fisheries, Faculty of Earth Science and Technology, Bandung Institute of Technology. Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat. [2]Ministry of Marine Affairs and Fisheries – Gedung Mina Bahari 3, 7th Floor, Jl. Merdeka Timur, Gambir, Jakarta Pusat, Indonesia.
- Email: *kamaluddin.kasim@gmail.com*
- ORCID: 0000-0001-5060-058X
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://www.researchgate.net/profile/Kamaluddin-Kasim

Radiarta, I.N., Ph.D., Instructor, Remote Sensing, [2]Ministry of Marine Affairs and Fisheries – Gedung Mina Bahari 3, 7th Floor, Jl. Merdeka Timur, Gambir, Jakarta Pusat, Indonesia.
- Email: *radiarta@gmail.com*
- ORCID: 0000-0002-8798-1344
- Web of Science ResearcherID: NA
- Scopus Author ID: 24341932700
- Homepage: https://www.researchgate.net/profile/Nyoman_Radiarta

HOW TO CITE THIS ARTICLE

Trenggono, S.W.; Meilano, I.; Latief, H.; Diantara, S.D.; Sakti, W.I.; Ketaren, D.G.K.; Winata, I.N.P.; Yuwono, T.; Syamdidi; Arthatiani, F.Y.; Kasim, K.; Radiarta, I.N., (2025). Innovation in the blue economy and environmental sustainability in marine and fisheries strategy. Global J. Environ. Sci. Manage., 11(2): 497-518.

DOI: 10.22034/gjesm.2025.02.08

URL: https://www.gjesm.net/article_719456.html

Global J. Environ. Sci. Manage. 11(2): 519-532, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Social acceptance of water quality through decentralized greywater treatment using green wall system

N. Obeidat[1,*], A. Abu-Awwad[1], A.S. Al-Salaymeh[2], J. AlBtoosh[3], M.M. Zoubi[4], Q.Y. Abu-Afifeh[1], M.A. Seif[5], H. Hroub[1], O. Arabiat[6]

[1] *Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan*

[2] *Mechanical Engineering Department, School of Engineering,The University of Jordan, Amman 11942, Jordan*

[3] *Waste Management Portfolio, Deutsche Gesellschaft fur Internationale Zusammenarbeit GmbH, Amman, Jordan*

[4] *Department of Chemistry, The University of Jordan, Amman 11942, Jordan*

[5] *School of Chemical and Biomolecular Engineering, The University of Sydney, Sydney, NSW 2006, Australia*

[6] *Environmental Studies and Planning Department, Greater Amman Municipality, Amman 11942, Jordan*

ARTICLE INFO

Article History:
Received 02 October 2024
Revised 06 December 2024
Accepted 10 January 2025

Keywords:
Community participation
Environmental management
Innovative systems
Social readiness
Sustainable solution
Water quality

ABSTRACT

BACKGROUND AND OBJECTIVES: Addressing water scarcity through innovative and sustainable solutions is crucial in regions like Jordan, where resources are limited, and community involvement plays a pivotal role in ensuring success. This study examines the social acceptance and readiness of university dormitory residents, specifically female students at Al-Zahra'a Dormitory, the University of Jordan, for implementing a decentralized greywater treatment system using green walls. This study seeks to examine the social factors influencing the deployment of decentralized greywater treatment systems, particularly focusing on enhancing public acceptance and ensuring their sustainable use in urban settings.

METHODS: This study investigated the technical capabilities of the greywater treatment system by analyzing the quality of the treated effluent against Jordanian standards, thereby evaluating its potential for reuse in toilet flushing and irrigation applications. Additionally, a structured questionnaire with 24 questions was distributed to dormitory residents and staff to explore social acceptance. Responses were categorized into four thematic groups: 1) Awareness and Understanding, assessing participants' familiarity with greywater treatment; 2) Perceptions and Attitudes, evaluating opinions and concerns regarding the system; 3) Environmental Impact, examining perceived benefits and potential drawbacks; and 4) Participation and Support, measuring willingness to engage in operation and maintenance activities. This mixed-methods strategy offered in-depth understanding of the technical viability and social interactions involved in the implementation of the system.

FINDINGS: The findings indicate that 90 percent of respondents are aware of water scarcity, with the majority strongly supporting innovative solutions like the green wall system. The study emphasizes the critical role of community participation in the success of sustainable systems. Notably, 82 percent of respondents expressed interest in training programs on the operation and maintenance of the greywater system, demonstrating a proactive attitude toward its long-term sustainability. Morever, 87 percent favored the expansion of the system from the dormitory to other residential neighborhoods, reflecting a strong consensus and the potential for more extensive application. However, concerns regarding potential issues such as odor and health impacts were noted, with nearly 50 percent of participants expressing discomfort.

CONCLUSION: Overall, strong community interest and readiness for green wall-based greywater systems highlight their potential to address water challenges. Continuous monitoring, system optimization, and stakeholder collaboration are essential for long-term success. By implementing well-defined protocols, offering thorough training, and optimizing management strategies, organizations can alleviate health and environmental concerns, which in turn cultivates trust among users. Expanding these systems to other areas with community involvement and outreach programs can amplify impact. Continued investigation into social acceptance will improve strategies and promote the broader implementation of decentralized greywater treatment solutions.

DOI: 10.22034/gjesm.2025.02.09

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
31	5	2

*Corresponding Author:
Email: *n.obeidat@ju.edu.jo*
Phone: +96279 730 4884
ORCID: 0009-0007-8481-9214

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Jordan, one of the driest countries in the world, faces severe water scarcity due to limited freshwater resources exacerbated by rapid population growth, urbanization, and climate change (Al-Karablieh and Salman, 2016; Al-Ansari *et al*., 2014). Per capita water consumption in Jordan remains significantly below the water scarcity threshold (Pedro-Monzonís et al., 2015; AlBtoosh *et al*., 2024), with growing competition for water among agricultural, industrial, and domestic sectors (Boano *et al*., 2019; Saxena *et al*., 2022). The use of alternative water resources, including treated wastewater, is essential for mitigating this crisis and is already prevalent in agricultural and industrial applications (MWI, 2024). Implementing these applications in urban settings for non-potable functions, including irrigation and toilet flushing, signifies a major progress toward sustainable water management. Decentralized wastewater treatment, which treats water near its source, offers a flexible and efficient solution for urban settings with limited space. Greywater, lightly contaminated wastewater from sinks and showers, is a particularly promising resource for reuse (Chfadi *et al*., 2021; Saxena *et al*., 2022). As a nature-based solution, green walls stand out as sustainable and energy-efficient options for treating greywater, presenting a viable alternative to conventional treatment methods (Rysulová *et al*., 2016). These systems not only address water scarcity but also enhance urban aesthetics, reduce the urban heat island effect, and improve air quality, fostering public support for their adoption (Bustami *et al*., 2023; Wright and Peterman, 2024). The viability of green wall systems is significantly influenced by social acceptance, with factors such as public perception, cultural attitudes, and community participation being key to their long-term success (Al-Khatib *et al*., 2022; López-Cabarcos *et al*., 2024). Studies have demonstrated that decentralized systems often foster greater community trust and engagement compared to centralized systems, as they allow for localized decision-making and greater alignment with community needs (Evans *et al*., 2012). Evidence from case studies in Mediterranean regions indicates that initiatives focused on community-led green walls can enhance sustainable development and encourage environmental accountability (Martinuzzi *et al*., 2022). Decentralized greywater treatment systems in Jordan have demonstrated considerable potential. Obeidat *et al*. (2024) evaluated a system in a rural household featuring an upflow anaerobic sludge blanket reactor and an unplanted vertical flow constructed wetland. This system achieved over 90 percent (%) removal efficiency for critical parameters such as including potential of hydrogen (pH), chemical oxygen demand (COD) milligrams per liter (mg/L), biochemical oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), Phosphorus (P), most probable number per 100 milliliters (MPN/100mL) and *Escherichia coli* (*E. coli*), meeting Jordanian Standards (JS) for greywater reuse in irrigation. The analysis emphasized the critical role of economical design in promoting accessibility and sustainability, while also highlighting the essential contribution of community engagement to the overall success of the system. Understanding the connection between social acceptance and system efficiency is essential. By involving residents in the planning, design, and maintenance of green walls, a sense of ownership is created, ensuring that the project aligns with local requirements. Furthermore, tackling concerns related to health risks and odors is key to fostering community trust (Sari et al., 2023). Educational initiatives, such as workshops, further enhance public understanding of the environmental and economic benefits, increasing adoption rates (Rysulová *et al*., 2016; Rysulová *et al*., 2017). Research shows that financial incentives, environmental awareness, and trust in water management authorities significantly influence public support for such initiatives (López-Cabarcos *et al*., 2024). Treated wastewater has become a vital alternative water source in Jordan, mainly serving agricultural and industrial sectors (MWI, 2024). Increasing the application of non-potable water in urban environments for purposes like irrigation and toilet flushing is a promising initiative toward enhancing water sustainability. However, the successful implementation of decentralized greywater treatment systems requires addressing social, cultural, and economic factors that influence public acceptance (Abu-Afifeh et al., 2023; Al-Afeshat et al., 2025). Implementing decentralized greywater treatment systems in urban areas of Jordan offers a significant chance to combat water scarcity and enhance environmental and social sustainability. These systems can exemplify sustainable water management in arid regions by merging technical efficiency with active community participation. The

study targeted residents of Al-Zahra'a Dormitory at the University of Jordan. Using a structured questionnaire, it examined awareness, perceptions, and attitudes toward the installed greywater treatment system, the environmental impact of greywater reuse, and the extent of community engagement. The aims of this study was to explore the social dynamics surrounding the implementation of decentralized greywater treatment systems, with a focus on fostering public acceptance and ensuring sustainable adoption in urban contexts. This study has been conducted in 2024 in Jordan.

MATERIALS AND METHODS

Study site description

A pilot-scale onsite decentralized greywater treatment system, primarily featuring green wall facades, was installed at Al-Zahra'a female dormitory on the University of Jordan campus as shown in Fig. 1. The university, located in an urban area of Amman, spans over 120 hectares (ha). Accommodating roughly 300 female students, the dormitory serves individuals from a wide range of academic fields and regions for ten months each year. It consists of three main residential blocks: Wing A, with three floors housing 108 students; Wing B, with four floors accommodating 160 students; and Wing C, currently closed for maintenance. Every wing is provided with common shower units, bathrooms, kitchen areas, and laundry facilities. The dormitory's water is primarily obtained from the municipal public network, with additional water tanks available to address any shortages that may arise.

Assessment of greywater treatment system performance

An evaluation was conducted to assess the technical performance of the greywater treatment system, focusing on its ability to effectively treat greywater in an urban context. The efficiency of a



Fig. 1: Geographic location of the study area in Al-Zahra'a female dormitory at the University of Jordan, Jordan

Table 1: Characteristics of raw and treated greywater as well as the greywater standards in Jordan (Obeidat *et al.,* 2024; Al Arni *et al.,* 2022)

Parameter	Green façade system		Jordan Standards	
	Influent	Effleunt	Irrigating cooked vegetables and other crops	Irrigating raw eaten
pH	8.19 ± 0.3	8.02 ± 0.2	6-9	6-9
TSS (mg/L)	47 ± 16	7 ± 3	100	50
COD (mg/L)	295 ± 59	27 ± 24	120	120
BOD (mg/L)	160 ± 55	14 ±14	60	60
TN (mg/L)	21.30 ± 6.4	8.51 ± 3.50	50	50
E. coli (MPN/100ml)	$(2.33 \pm 2.5)\times10^5$	$(2.45 \pm 1.1)\times10^2$	10^4	10^3

green wall-based greywater treatment system was evaluated using several key metrics: reductions in BOD, COD, TSS, and pathogens to measure the removal of organic pollutants, suspended solids, and harmful microorganisms, ensuring water safety; nutrient removal to prevent environmental harm like eutrophication; pH and salinity levels to confirm compatibility with reuse applications. By calculating the percentage reductions of critical contaminants, we obtained a clear and quantifiable assessment of the system's performance. To ensure consistent treatment conditions, hydraulic retention time (HRT) was maintained at a fixed level. A balanced HRT ensures effective contaminant removal while maintaining system throughput and preventing overloading. During the preliminary stages, plant health and biomass growth were evaluated visually, while more in-depth monitoring is intended for future studies. Another measure was Water Reuse Suitability (Compliance with Standards). The final treated effluent was compared with the JS (1776/2013) and JS (893/2021) to determine its suitability for irrigation and toilet flushing within the University of Jordan, including applications such as toilet flushing and irrigating lawns and parking areas. The green façade system is designed to treat approximately 4.8 cubic meters (m^3) of greywater per day, specifically from showers and wash basins. In order to control the permitted flow rate of the system, the plumbing fixtures have been appropriately divided. The central sewer network receives black water, multiple sources of greywater, and any additional light greywaterThis study did not include measurements of energy consumption; however, it can be readily integrated into future study initiatives. However, the system requires electrical energy to operate the pumps that automatically control water flow. Additionally, solar panels are part of the university's solar energy project, helping to reduce energy consumption. Renewable solar energy is also used as a key resource for plant growth, as the plants depend on the treated water for nourishment. The positioning of the green wall façades has been carefully planned to enhance sunlight exposure, which is essential for the healthy growth of the plants. Future planning will continue to incorporate renewable energy sources to further enhance the system's sustainability. The characteristics of raw and treated greywater, as well as the relevant greywater standards in Jordan, are detailed in Table 1.

Social evaluation of greywater treatment system implementation

The study focused on the social aspects of implementing the treatment system. A comprehensive questionnaire consisting 24 questions was designed to assess the awareness, perceptions, and acceptability of the system among the female residents and staff within the dormitory. The questionnaire responses were categorized into four groups as show in Table 2.

1. Awareness and Understanding (Q1–Q4): Assessed participants' familiarity with and knowledge of greywater treatment.
2. Perceptions and Attitudes (Q5–Q12): Evaluated their opinions and views toward the system.
3. Environmental Impact (Q13–Q20): Examined their perceptions of the system's environmental benefits and potential drawbacks.
4. Participation and Support (Q21–Q24): Measured their willingness to engage with and support the system's operation and maintenance.

By merging technical and social evaluations, a detailed perspective on the system's functionality and its approval by the dormitory residents was achieved.

To achieve a statistically representative sample size, the sampling methodology was developed with

Table 2: Questions provided for assessed awareness and understanding, perceptions and attitudes, environmental impact and participation and support groups

Group	Question	Rationale/Intent
Awareness and understanding	1. Are you aware of water scarcity status in Jordan?	To evaluate the initial understanding of participants regarding the essential factors that necessitate sustainable water management solutions.
	2. Do you believe you understand the idea behind the gray water treatment system that uses green walls in Al-Zahraa dormitory for female students?	To evaluate participants' familiarity with the system concept and its objectives.
	3. Do you believe you have a thorough understanding of how the green walls in the student residence's grey water treatment system operate?	To identify gaps in technical knowledge and understanding of system functionality.
	4. Do you believe that treating grey water at the Zahra residence for female students using an on-site decentralized green wall system is a novel and successful solution?	To gauge perceptions of the system's innovation and effectiveness.
Perception and attitude	5. Do you believe it is necessary to replace the current dorm wastewater management practice with an alternative approach involving wastewater treatment and reuse?	To evaluate the support for transitioning to sustainable water management approaches.
	6. Would you like to have a training program in your residential area for the purpose of training local people to build and maintain onsite greywater treatment units?	To assess interest in capacity-building initiatives to promote community-led sustainability efforts.
	7. If the greywater treatment system is installed on site in your yard, will you be willing to reuse the treated greywater to irrigate the home garden?	To evaluate willingness to adopt greywater reuse practices at a personal level.
	8. Would you like to be more involved in the decision-making process regarding the dorm sustainability initiatives?	To determine the desire for greater participation in sustainability decision-making.
	9. Would you like to transfer this on-site greywater treatment experience to the perimeter of your residence?	To measure interest in scaling the system beyond the dormitory.
	10. Do you support reusing treated greywater for specific purposes (such as agriculture irrigation, toilet flushing)?	To understand participants' attitudes toward specific applications of treated greywater.
	11. Are you worried about any issues or difficulties regarding the use of the treatment system?	To identify perceived barriers or concerns related to the system's operation.
	12. Would you be willing to adopt your water usage habits to meet the objectives of the treatment system?	To examine the readiness to implement behavioral adjustments necessary for achieving system objectives.
Environmental impact	13. Do you believe that treating and reusing greywater in the dorm using an on-site green wall system would enhance the availability of water?	To evaluate perceptions of the system's potential impact on water availability.
	14. Do you think that the aesthetic aspect of implementing the system in Al Zahra dorm has overcome any potential issues such as the emission of odors (if they exist)?	To assess whether aesthetic benefits help offset operational concerns like odors.
	15. Did you feel that the treatment system of green walls that installed on the exterior facades of the building added aesthetic attractiveness to the outdoor areas?	To evaluate perceptions of the system's contribution to the dorm's aesthetics.
	16. Has the treatment system issued any disturbing odors or gathering of mosquitoes that necessitated a complaint by the system's officials?	To document operational challenges such as odors or pests that impact user experience.
	17. Have you experienced any environmental or health issues as a result of using the system?	To identify any adverse impacts of the system on health or the environment.
	18. Do you think the system has created additional green spaces that could be used as seating areas?	To assess whether the system contributes to functional and recreational green spaces.
	19. Are you aware of the significance of water conservation and environmental sustainability for the dorms?	To measure awareness of broader sustainability goals linked to the system.
	20. Do you have any problems with water shortages or restrictions on their use in the area of your stay?	To establish the prevalence of water scarcity issues among participants.
Participation and support	21. Do you believe that the implementation of the green wall system to treat and reuse greywater can encourage sustainable behavior among female students in dormitory?	To determine if the system promotes the development of sustainable habits within the community.
	22. Would you be interested in attending educational courses or workshops regarding the beneficial effects of decentralized grey water treatment systems as well as their correct setup, management, and operation?	To assess interest in educational initiatives aimed at promoting system understanding and engagement.
	23. Would you be willing to support the implementation of the system in the dorm?	To measure overall support for adopting the system in the dormitory.
	24. Have administrators of the system reacted to collect any feedback or resolve any issues arising from the use of the system?	To evaluate the responsiveness of administrators in addressing user concerns and fostering trust.

consideration for the population of approximately 300 female residents at the Al-Zahra'a dormitory. A total of 190 residents out of 300 participated in the social survey, with the sample size determined using Eq. 1 (Daniel, 1999):

$$n = \frac{N \times Z^2 \times p \times (1-p)}{\left(d^2 \times (N-1)\right) + \left(Z^2 \times p \times (1-p)\right)} \quad (1)$$

Where, n is the sample size, N is the population size (300), Z is the Z statistic for a 95% confidence level (Z = 1.96), p is the expected prevalence or proportion (p = 0.5) and d is the precision (5%). In line with Daniel's (1999) findings, a proportion (pp) of 0.5 was employed to enhance the sample size, since this proportion results in the largest sample size possible for a specified confidence level and margin of error. This conservative approach ensures that the sample is sufficiently large to capture variability within the population, even in the absence of prior knowledge about the true proportion. Montgomery and Runger (2007) were referenced to ascertain the Z-value of 1.96 for a confidence level of 95%. Substituting these values into the formula, the calculated sample size was approximately 169 participants. In order to bolster the dependability of the findings and mitigate the effects of potential non-responses, the sample size expanded to 190 participants. This adjustment provides additional confidence in the representativeness of the sample and ensures robust statistical analysis. The final sample of 190 participants not only exceeded the minimum requirement but also represented 63% of the total population of 300 dormitory residents. This high proportion of participation reinforces the validity of the results, providing a comprehensive overview of residents' perceptions and attitudes toward the greywater treatment system. Through the application of a meticulous sampling approach, the research ensured that the data gathered was representative and trustworthy, encompassing the diverse opinions within the dormitory community.

RESULTS AND DISCUSSION

The study's results reveal both the technical and social dimensions of the decentralized greywater treatment system implemented at Al Zahra'a dormitory. The primary focus of this study is social evaluation, which underscores the need to grasp residents' awareness, perceptions, attitudes, and their willingness to participate in these systems, as these factors are vital for ensuring their enduring viability.

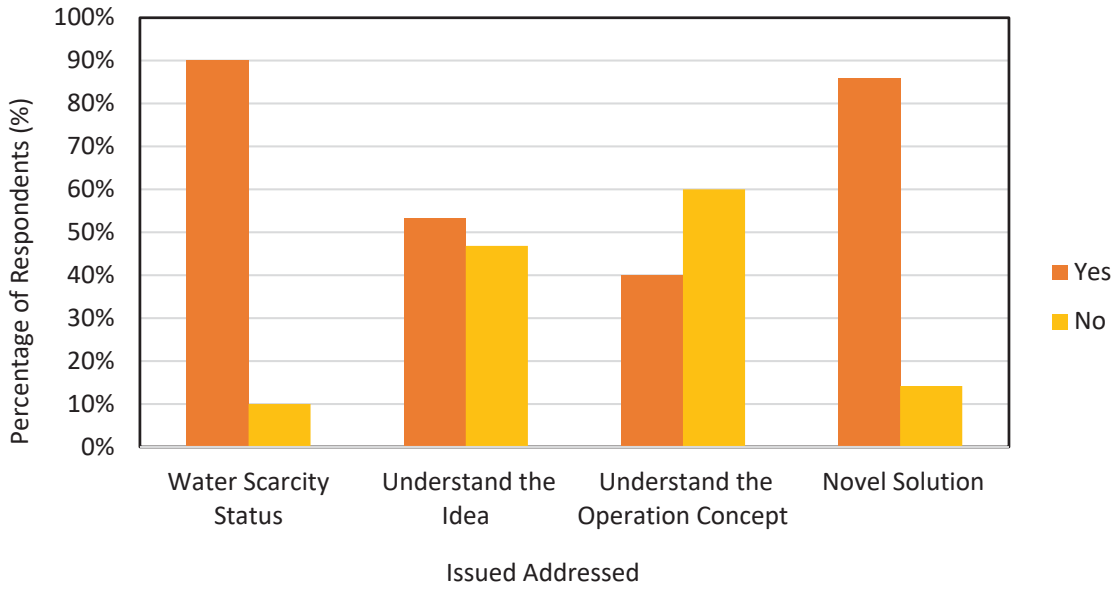


Fig. 2: Results of the social awareness and understanding part

Social awareness and understanding

Jordan's chronic water scarcity necessitates innovative solutions that optimize resource use. By implementing a greywater treatment system that incorporates green walls, this approach directly confronts the issue by allowing for water reuse, lessening the strain on freshwater resources, and fostering sustainable lifestyle choices. Its feasibility and social acceptance highlight its potential as a cornerstone for advancing water conservation in urban areas. The evaluation focused on the understanding and interest of staff and female students at Al Zahra'a dormitory, University of Jordan, in relation to greywater treatment and its potential applications. Through questions assessing awareness, understanding, and perceptions, the results revealed that 90% of respondents were aware of Jordan's water scarcity challenges (Fig. 2). This aligns with findings by Cagno *et al.* (2022), who highlighted the significance of local awareness in fostering support for water reuse technologies. However, the remaining 10% of respondents were unaware of the issue, underscoring an educational gap and the need for targeted awareness programs, as similarly noted by Singha *et al.* (2022). In response to inquiries regarding the greywater treatment system that incorporates green walls, only 53% of participants expressed comprehension of the concept, and just 40% had knowledge of its particular operations. This limited understanding could hinder the system's maintenance and success, consistent with observations by Lanchipa-Ale *et al.* (2024), who emphasized user education as critical to the effective adoption of such systems. In spite of the existing knowledge gaps, 86% of participants regarded green walls as a pioneering approach to greywater treatment, indicating a significant interest in sustainable technologies. Educational programs should focus on system operation, maintenance, and environmental benefits, targeting gaps in technical knowledge. The combination of interactive workshops, experiential training, and ongoing feedback sessions can cultivate a more profound understanding and encourage lasting commitment. Drawing from successful implementations in arid regions, incorporating community-led discussions and peer-led training can strengthen trust and participation. Engaging female students in leadership roles within training and outreach programs can channel their enthusiasm and contribute to the development of a sustainable culture. Long-term maintenance will be supported by university staff, with periodic evaluations to ensure system continuity and resolve gaps in community involvement.

Perception and attitudes

In the second segment of the survey focused on perceptions and attitudes, it was found that 86% of participants were in favor of transitioning from current wastewater management practices to alternative systems that integrate treatment and reuse. This aligns with Akpan *et al*. (2020), who highlighted growing public interest in sustainable wastewater management, particularly when linked to water conservation and environmental sustainability benefits. Likewise, 82% of respondents showed enthusiasm to participate in training programs aimed at the implementation and upkeep of on-site greywater treatment systems, highlighting a significant readiness to embrace sustainable practices (Fig. 3). An impressive 88% showed interest in using treated greywater for home garden irrigation, demonstrating robust support for water-saving initiatives. Moreover, 87% of respondents expressed a desire for greater influence in dorm sustainability decisions, emphasizing the critical role of community engagement in successful sustainability projects, as noted by Syme *et al*. (2002). Furthermore, 87% of participants favored the extension of the greywater treatment system to adjacent residential neighborhoods, underscoring the community's willingness to adopt more comprehensive sustainable water management practices. Despite these positive attitudes, 74% of participants voiced concerns about potential operational challenges, indicating a need to address perceived barriers and provide reassurance about the system's reliability. It is noteworthy that 90% of participants indicated a willingness to change their water usage behaviors in order to meet the goals set by the greywater treatment system.. This demonstrates strong community buy-in for behavioral changes essential to achieving sustainable water management, consistent with findings by Carrico *et al*. (2011). To alleviate operational issues such as odors and pest problems, implementing sophisticated filtration, optimizing ventilation, and employing specific pest control measures can be highly effective. Scheduled maintenance routines and

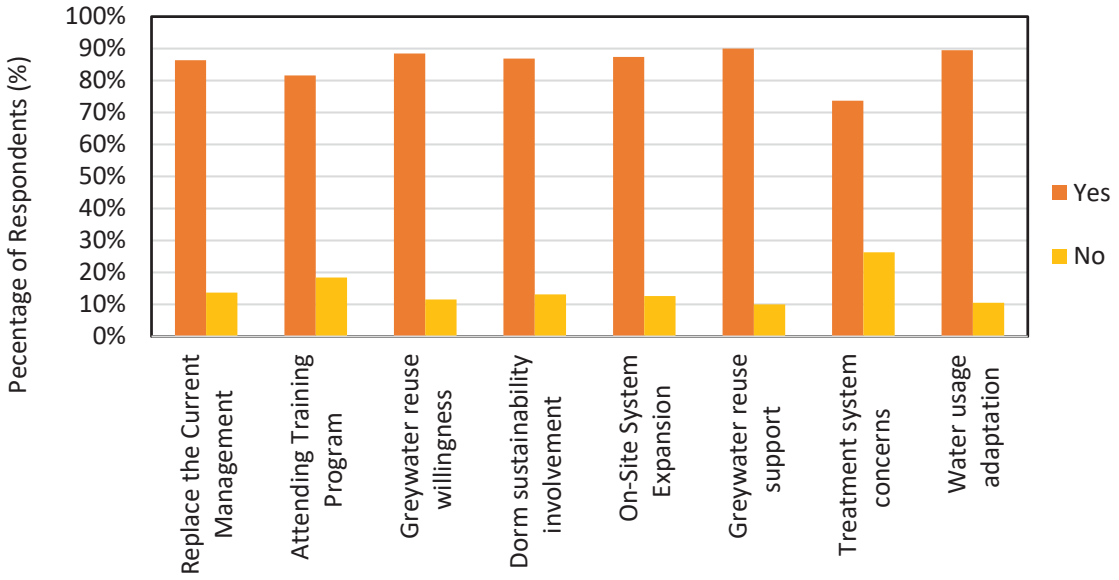


Fig. 3: Results of the perception and attitude's part

mechanisms for community feedback guarantee that issues are addressed in a timely manner. Leveraging internet of things (IoT)-enabled sensors for water quality and system performance monitoring provides a cost-effective way to enhance reliability and user satisfaction.

Environmental impact

The third part of the survey focused on the environmental effects of the greywater treatment system, revealing that an impressive 92% of participants supported the use of the green wall system for the treatment and reuse of greywater (Fig. 4). This strong support aligns with previous findings, such as those by Saxena *et al*. (2022), which highlighted widespread recognition of greywater reuse systems' environmental benefits, particularly in reducing freshwater consumption. Furthermore, 88% of participants expressed their satisfaction with the visual improvements that the green wall system brought to the outdoor areas of the dormitory, while 79% concurred that the system successfully tackled problems related to odor emissions. However, challenges persisted, with 48% of participants reporting occasional unpleasant odors or mosquito infestations and 49% encountering health or environmental concerns related to the system's operation. These challenges echo findings by Lanchipa-Ale *et al.* (2024), who emphasized the need to address practical issues, such as maintenance and system reliability, for long-term viability. Despite these concerns, 86% of respondents believed the system improved the variety of green spaces, creating valuable recreational areas for students. Moreover, 96% of participants recognized the importance of environmental sustainability and water conservation efforts within the dormitory, reflecting a high level of community support. Significantly, 64% of participants indicated that they faced water scarcity while they were present, highlighting the urgent requirement for sustainable water management strategies. These observations align with Syme *et al.* (2002), who found that firsthand experiences with water scarcity often strengthen public support for conservation technologies. Scaling greywater systems requires addressing logistical constraints like infrastructure availability and financial limitations. A step-by-step approach to implementation, combined with alliances with local stakeholders, can promote a smooth transition. Further research into site-specific challenges and user behavior will refine strategies for broader application (Al-Addous *et al*., 2023).

Participation and support

The concluding part of the survey, which focused on the participation and endorsement of the

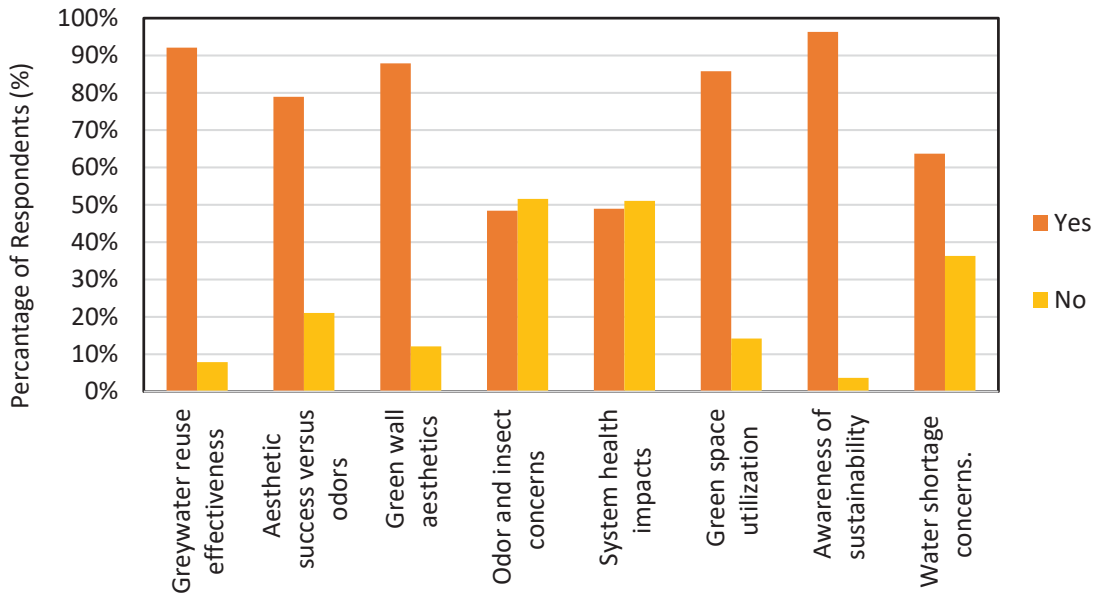


Fig. 4: Results of the environmental impact part

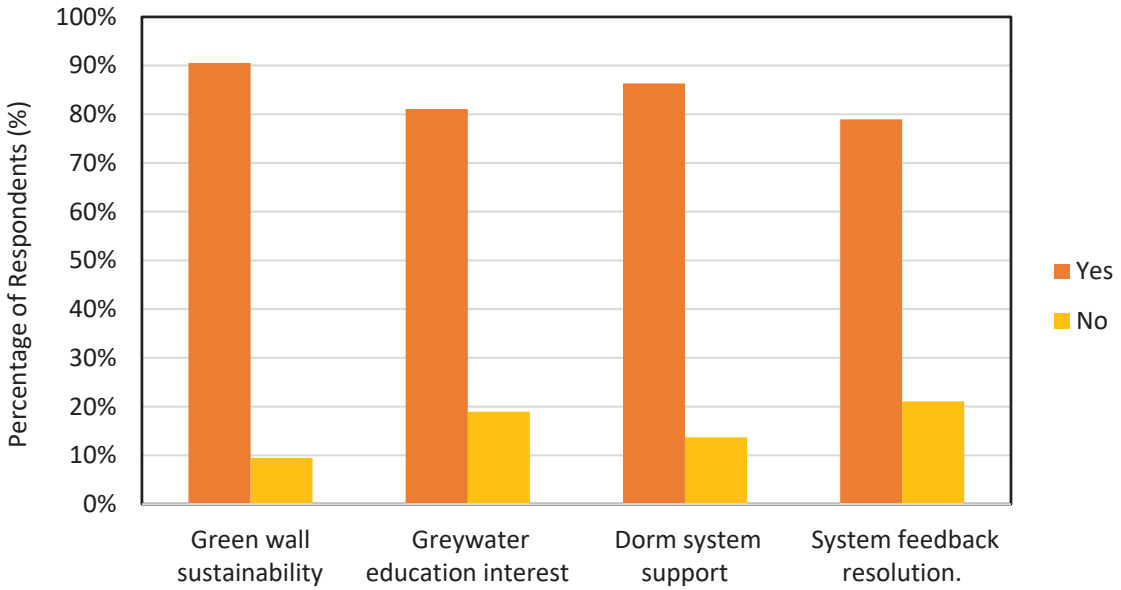


Fig. 5: Results of the participation and support part

greywater treatment system (Fig. 5), revealed that 91% of female residents showed robust support for its installation. This significant level of endorsement aligns with findings by Baawain *et al.* (2020), who emphasized the growing public recognition of the environmental benefits associated with sustainable practices. Furthermore, 81% of participants expressed a desire to participate in workshops or training sessions, highlighting the significance of active community involvement for the successful operation and maintenance of the system. Moreover, 85% of participants stated their support for implementing the greywater treatment system within the dormitory, while 79% acknowledged that administrators had

been responsive to their feedback and concerns about the system's operation. These outcomes underscore the significance of proficient administration and open communication in cultivating community trust and promoting active engagement, in agreement with the observations made by Lockwood *et al.* (2010).

CONCLUSION

This study at Al-Zahra'a dormitory underscores the feasibility and broad social acceptance of implementing greywater treatment systems utilizing green walls in urban settings. The results demonstrates a significant potential for sustainability, supported by strong community engagement, while pinpointing key areas that require enhancement, particularly in the realms of community education and system design refinement. Notably, the study provides novel insights into the proactive interest and engagement of female students, highlighting their potential as leaders in advancing sustainability initiatives. Despite 90% of residents acknowledging Jordan's water scarcity challenges, a pronounced knowledge gap regarding the technical operation of greywater systems was evident. Targeted educational initiatives have been identified as a crucial strategy to bridge this gap, with 82% of respondents indicating a strong interest in training programs centered on system operation and maintenance. This level of readiness presents an opportunity to develop a proficient and driven user base, crucial for the enduring success of the system. A unique contribution of this research is its exploration of operational challenges, including odors, mosquitoes, and health concerns, reported by nearly half of participants. These results underscore the importance of developing new design approaches, such as sophisticated filtration, optimized ventilation, and comprehensive pest control strategies, to effectively and affordably meet user needs. Additionally, regular assessments of water quality and system functionality are essential for ensuring compliance with reuse standards and maintaining operational efficiency. The study also highlights the transformative potential of green wall systems to integrate environmental sustainability with social well-being. Nearly 87% of participants supported extending the system to other residential areas, reflecting a broad readiness to embrace decentralized greywater treatment solutions. This extensive endorsement of these systems, combined with a robust enthusiasm for their education and training, positions them as practical instruments for combating water scarcity at both local and regional scales. Collaboration with stakeholders—including university administrators, water authorities, and environmental organizations—emerged as another critical insight. Such partnerships can streamline system implementation, secure funding, and enhance community outreach, ensuring sustained engagement and long-term impact. The emphasis on community ownership through clear protocols, feedback mechanisms, and routine training is vital for ensuring smooth operations and building trust. To conclude, this study presents innovative findings regarding the social and technical facets of greywater treatment systems that incorporate green walls, underlining their capacity to tackle water scarcity challenges and enhance community involvement. Expanding these systems to diverse urban and rural settings, supported by comprehensive education, system refinements, and stakeholder collaboration, holds promise for broader adoption. Future research should focus on refining these strategies and exploring their applicability across varied socio-economic and geographic contexts to maximize their impact. The effective establishment of greywater systems relies on comprehensive regulatory frameworks that support decentralized water management practices. Collaboration among administrators, environmental organizations, and funding agencies can secure resources, streamline training, and establish protocols for scaling, ensuring long-term sustainability. Financial incentives, including subsidies and grants, can lower adoption barriers and encourage widespread use of greywater systems. Engaging with municipal governments and global agencies can facilitate the acquisition of vital funding to successfully enhance these initiatives.

AUTHOR CONTRIBUTIONS

N. Obeidat played a central role in the study, contributing to conceptualization, methodology design, and performing the formal analysis. M.M. Zoubi was instrumental in the investigation, validation, and preparation of the original draft. A. Al-Salaymeh oversaw project administration and provided supervision throughout. Q.Y. Abu-Afifeh contributed by providing resources and and M.A. Seif by managing data curation. H. Hroub was

responsible for software aspects and O. Arabiat was responsible for visualization aspects. A. Abu-Awwad handled manuscript review while J. AlBtoosh handled manuscript editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
d	The precision
E. coli	Escherichia coli
ha	hectares
HRT	Hydraulic retention time
IoT	Internet of things
JS	Jordanian standards
m^3	cubic meters
m^3/d	cubic meters per day
mg/L	milligrams per liter
MPN/100mL	Most probable number per 100 milliliters
n	The sample size
N	The population size
NBS	Nature-based solutions
p	The expected prevalence or proportion
TN	Total Nitrogen
TSS	Total Suspended Solids
Z	The Z statistic for a 95% confidence level

REFERENCES

Abu-Afifeh, Q.; Rahbeh; M.; Al-Afeshat, A.; Al-Omari, S.; Qutishat, T.A.; Brezat, A.; Alkayed, A., (2023). Dam sustainability's interdependency with climate change and dam failure drivers. Sustainability., 1: 1-19 **(19 pages)**.

Akpan, V.E.; Omole, D.O.; Bassey, D., (2020). Assessing the public perceptions of treated wastewater reuse: opportunities and implications for urban communities in developing countries. Heliyon. 6: 1-22 **(22 pages).**

Al Arni, S.; Elwaheidi, M.; Salih, A.A.M.; Ghernaout, D.; Matouq, M., (2022). Greywater reuse: an assessment of the Jordanian experience in rural communities. Water Sci. Technol., 85: 1952–1963 **(12 pages).**

Al-Addous, M.; Bdour, M.; Alnaief, M.; Rabaiah, S.; Schweimanns, N., (2023). Water resources in Jordan: a review of current challenges and future opportunities. Water. 15(21): 3729 **(34 pages).**

Al-Afeshat, A.; Zoubi, M.M.; Abu-Afifeh, Q.Y.; Al-Jawaldeh, H.; Qutishat, T.A.; Masoud, A.M.N.; Rahbh, M., (2025). Interrelation of dams sustainability with the local communities and water quality. Global J. Environ. Sci. Manage., 11(1): 157-176 **(20 pages)**.

AlBtoosh, J.; Abu-Awwad, A.; Obeidat, N. (2024). A Statistical approach to the water scarcity implications on food security. Global J. Environ. Sci. Manage., 10: 201-218 **(18 pages).**

Al-Karablieh, E.; Salman, A., (2016). Water resources, use and management in Jordan. A focus on groundwater. International Water Management Institute.

Al-Khatib, I.A.; Al Shami, A.A.H.U.; Rodriguez-Garcia, G.; Celik, I., (2022). Social acceptance of greywater reuse in rural areas. J. Environ. Public Health. 2022(3): 1-11 **(11 pages).**

Baawain, M.S.; Al-Mamun, A.; Omidvarborna, H.; Al-Sabti, A.; Choudri, B.S., (2020). Public perceptions of reusing treated wastewater for urban and industrial applications: challenges and opportunities. Environ. Dev. Sustainability. 22: 1859–1871 **(13 pages).**

Boano, F.; Caruso, A.; Costamagna, E.; Fiore, S.; Demichelis, F.; Ridolfi, L.; Galvão, A.; Pisoeiro, J.; Rizzo, A.; Masi, F., (2019). Greening walls for treatment and reuse of domestic greywater. Sci. Total Environ., 671: 1168-1179 **(12 pages).**

Bustami, R.A.; Rawlings, R.; Beecham, S.; Ward, J.; Mah, D. Y. S., (2023). Living walls in the city: community values and expectations. Int. J. Integr. Eng., 15(6): 79-86 **(10 pages).**

Cagno, E.; Garrone, P.; Negri, M.; Rizzuni, A., (2022). Adoption of water reuse technologies: an assessment under different regulatory and operational scenarios. J. Environ. Manage., 317: 115389 **(13 pages)**.

Carrico, A.R.; Riemer, M., (2011). Motivating energy conservation in the workplace: an evaluation of the use of group-level feedback and peer education. J. Environ. Psychol., 31(1): 1-13 **(13 pages).**

Chfadi, T.; Gheblawi, M.; Thaha, R., (2021). Public acceptance of wastewater reuse: new evidence from factor and regression analyses. Water. 13(10): 1391 **(18 pages).**

Daniel; W.W., (1999). Biostatistics: a foundation for analysis in the health sciences. John Wiley.

Evans, C.; Anda, M.; Dallas, M.; Ho, G., (2012). Demonstration of decentralised wastewater recycling in urban villages in Western Australia. Conference: Singapore International Water Week.

Lanchipa-Ale, T.; Cruz-Baltuano, A.; Molero-Yañez, N.; Chucuya, S.; Vera-Barrios, B.; Pino-Vargas, E., (2024). Assessment of greywater reuse in a university building in a hyper-arid region: quantity, quality, and social acceptance. Sustainability. 16: 3088 **(25 pages).**

Lockwood, M.; Davidson, J.; Curtis, A.; Stratford, E.; Griffith, R., (2010). Governance principles for natural resource management. Soc. Nat. Resour., 23(10): 986-1001 **(16 pages).**

López-Cabarcos, M.Á.; Piñeiro-Chousa, J.; Quiñoá-Piñeiro, L.; López-Pérez, M.L., (2024). Water and Waste Management Strategies as Drivers of the Financial Performance of Food Companies. Technol. Forecast. Soc. Change. 200: 123138 **(11 pages).**

Martinuzzi, N.; Rivai, K.; Rizzo, A.; Masi, F.; Sarnari, B.; Bousselmi, L., (2022). Green walls for greywater treatment and reuse in mediterranean countries. 17th International Conference on Environmental Science and Technology.

Montgomery, D. C.; Runger, G. C., (2007). Applied statistics and probability for engineers. John Wiley and Sons, Inc.

MWI, (2024). Annual reports and dams. Ministry of Water and Irrigation, Amman, Jordan.

Obeidat, N.; Shatanawi, K.; Kassab, G.; Halalsheh, M. (2024). Performance of decentralized wastewater treatment system employing upflow anaerobic sludge blanket and vertical flow constructed wetland. Case Stud. Chem. Environ. Eng., 9: 100695 **(10 pages).**

Pedro-Monzonís, M.; Solera, Abel.; Ferrer, J.; Estrela, T.; Paredes-Arquiola,J., (2015). A review of water scarcity and drought indexes in water resources planning and management. J. Hydrol., 527: 482-493 **(12 pages).**

Rysulová, M.; Kaposztasova, D.; Vranayová, Z., (2017). Green walls as an approach in grey water treatment. IOP Conference Series: Materials Science and Engineering. 245(7):072049.

Rysulová, M.; Kaposztasova, D.; Vranayová, Z.; Castellar, J.; Morató, J., (2016). Turning grey into green – integration of living walls in grey water systems. In The 2nd International Conference on Engineering Sciences and Technologies**.**

Sari, R.; Soytas, U.; Kanoglu-Ozkan, D.G.; Sivrikaya, A., (2023). Improving the climate resilience of European cities via socially acceptable nature-based solutions. NPJ Urban Sustainability. 3(9): 1-13 **(13 pages).**

Saxena, R.; Srivastava, N.; Ansari, S.; Rai, P.K.; Singh, N.; Maurya, V.K., (2022). The role of government in urban water management. Curr. Dir. Water Scarcity Res., 6: 341-359 **(19 pages).**

Singha, B.; Eljamal, O.; Karmaker, S.C.; Maamoun, I.; Sugihara, Y., (2022). Water conservation behavior: exploring the role of social, psychological, and behavioral determinants. J. Environ. Manage., 317(115484): 1-28 **(28 pages).**

Syme, G. J.; Nancarrow, B. E., (2002). Evaluation of public involvement programs: Measuring justice and process criteria. Water. 29(4): 18-24 **(7 pages).**

Wright, N.; Peterman, K.D., (2024). Green walls: a review of their thermal mechanisms, efficacy, and performance. SSRN. 1-26 **(26 pages).**

AUTHOR (S) BIOSKETCHES

Obeidat, N., Ph.D., Instructor, Water and Environment Engineering, Department of Land, Water, and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *n.obeidat@ju.edu.jo*
- ORCID: 0009-0007-8481-9214
- Web of Science ResearcherID: LXA-7803-2024
- Scopus Author ID: 58952978400
- Homepage: https://agriculture.ju.edu.jo/Home.aspx

Abu-Awwad, A., Ph.D., Professor, Agricultural and Irrigation Engineering. Department of Land, Water, and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *abuawwad@ju.edu.jo*
- ORCID: 0000-0001-8992-9518
- Web of Science ResearcherID: KWU-9732-2024
- Scopus Author ID: 6603923220
- Homepage: http://eacademic.ju.edu.jo/abuawwad/default.aspx

Al-Salaymeh, A.S., Ph.D., Professor, Mechanical Engineering, Mechanical Engineering Department, School of Engineering, The University of Jordan, Amman 11942, Jordan.
- Email: *salaymeh@ju.edu.jo*
- ORCID: 0000-0002-2496-2138
- Web of Science ResearcherID: Q-3578-2019
- Scopus Author ID: 6603150758
- Homepage: https://eacademic.ju.edu.jo/salaymeh/default.aspx

AlBtoosh, J., Ph.D Candidate, Project Manager, Waste Management Portfolio, Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH, Amman, Jordan.
- Email: *jomanah.albtoosh@giz.de*
- ORCID: 0009-0006-5194-2200
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://www.giz.de/en/worldwide/360.html

Zoubi, M.M., M.Sc., Instructor, Chemistry, Department of Chemistry, The University of Jordan, Amman 11942, Jordan.
- Email: *mutazalzoubi@outlook.com*
- ORCID: 0009-0001-7719-8268
- Web of Science ResearcherID: LMP-2898-2024
- Scopus Author ID: 59008125300
- Homepage: https://science.ju.edu.jo/home.aspx

Abu-Afifeh, Q.Y., Ph.D., Instructor, Water and Environment Engineering, Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *qusayyabuafifeh@outlook.com*
- ORCID: 0000-0003-4451-3118
- Web of Science ResearcherID: LMO-4400-2024
- Scopus Author ID: 57219483554
- Homepage: https://agriculture.ju.edu.jo/Home.aspx

Seif, M.A., M.Sc., Instructor, Chemical and Biomolecular Engineering, School of Chemical and Biomolecular Engineering, The University of Sydney, Sydney, NSW 2006, Australia.
- Email: *m.saif93@outlook.com*
- ORCID: 0009-0002-0013-7747
- Web of Science ResearcherID: LZE-2350-2025
- Scopus Author ID: NA
- Homepage: https://www.sydney.edu.au/engineering/schools/school-of-chemical-and-biomolecular-engineering1.html

Hroub, H., Ph.D. Candidate, Instructor, Water and Environment Engineering, Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan.
- Email: *haneenhroub835@gmail.com*
- ORCID: 0009-0008-6487-4301
- Web of Science ResearcherID: LXA-7755-2024
- Scopus Author ID: NA
- Homepage: https://agriculture.ju.edu.jo/Home.aspx

AUTHOR (S) BIOSKETCHES

Arabiat, O., Ph.D., Instructor, Environmental Studies and Planning Department, Greater Amman Municipality, Amman 11942, Jordan.
- Email: *omar.ar@ammancity.gov.jo*
- ORCID: 0000-0002-5325-4755
- Web of Science ResearcherID: LZE-2389-2025
- Scopus Author ID: NA
- Homepage: https://media.ammancity.gov.jo/EN/ListDetails/Sectors_and_Directorates/1099/11

HOW TO CITE THIS ARTICLE

Obeidat, N.; Abu-Awwad, A.; Al-Salaymeh, A.; AlBtoosh, J.; Zoubi, M.M.; Abu-Afifeh, Q.Y.; Seif, M.A.; Hroub, H.; Arabiat, O., (2025). Social acceptance of water quality through decentralized greywater treatment using green wall system. Global J. Environ. Sci. Manage., 11(2): 519-532.

DOI: 10.22034/gjesm.2025.02.09

URL: https://www.gjesm.net/article_719778.html

Global J. Environ. Sci. Manage. 11(2): 533-554, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Modeling the effects of land use change on agricultural carrying capacity and food security

R. Harini[1,*], R. Rijanta[2], E.H. Pangaribowo[1], R.F. Putri[1], I. Sukri[3]

[1] *Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia*

[2] *Department of Development Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia*

[3] *Department of Geography, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Makassar, Indonesia*

ARTICLE INFO

Article History:
Received 29 September 2024
Revised 04 December 2024
Accepted 07 January 2025

Keywords:
Carrying Capacity
Cellular automata (CA)
Food security
Land use change (LUC)
Prediction

ABSTRACT

BACKGROUND AND OBJECTIVES: Food security is a global issue outlined in the sustainable development goals. Challenges concerning food are linked to the accessibility of food supplies. As the population continues to rise, the amount of agricultural land available for food production is on the decline. Changing agricultural land to built-up land causes problems in food security and the land's carrying capacity. The objective of this study is to identify shifts in land use and to utilize simulation models to anticipate future land use changes within the Special Region of Yogyakarta, along with assessing their implications for the region's agricultural land carrying capacity and food security. Predictions of spatial land changes will reveal changes in land function, carrying capacity and food security between regions.
METHODS: Land changes were studied using remote sensing imagery-based mapping methods and spatial simulations using the cellular automata approach. The land change map illustrates the spatial distribution of agricultural land that has changed.Spatial simulation was carried out using the cellular automata algorithm, through computers and spatial data processing software. To determine how well rice fields can satisfy the food demands of the population, the carrying capacity of agricultural land is analyzed. This process entails a comparison between the available land and the land required for agricultural purposes. Meanwhile, the calculation of food security uses a methodology adopted from the food security and vulnerability atlas method.
FINDINGS: Prediction results showed that the special region of Yogyakarta's built-up land area will expand between 2026 and 2034. The land carrying capacity will decline with the expansion of the built-up area, which will primarily be converted from agricultural land. While the carrying capacity of agricultural land has risen, food security has unfortunately declined. To bolster sustainable food security, it is essential to protect agricultural land and adopt modern agricultural innovations that can further increase its carrying capacity. The carrying capacity of the agricultural land in the special region of Yogyakarta between 2018 and 2022 ranged from 0.0026 to 1.034. In 2018, most areas in this region had high food security. Yogyakarta City was the only city in 2018 with the lowest food security at 66.34. In 2022, Kulon Progo Regency and Sleman Regency had a lower food security level than the previous year.
CONCLUSION: This study explores land use change, land carrying capacity, and food security in the Special Region of Yogyakarta, Indonesia. Due to population expansion and various development projects, land conversion is a necessary process, and the transition of agricultural land into urban environments jeopardizes food sources. The study uses food security and vulnarebility atlas mapping indicators, agricultural land carrying capacity, and food security to explain the complex interactions. Cellular automata predicts land use changes, showing the highest land use change in 2034 directly impacts land carrying capacity and food security. To achieve food security and sustainable agricultural development, proactive measures are crucial. The insights gained from this research can serve as a foundation for future investigations and policy actions that seek to bolster food security and support sustainable agricultural practices.

DOI: 10.22034/gjesm.2025.02.10

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
80	7	9

*Corresponding Author:
Email: *rikaharini@ugm.ac.id*
Phone: +62815 790 7969
ORCID: 0000-0002-2801-5111

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Food security has become a pressing issue due to the medication of the environment's carrying capacity, the loss of agricultural land, and the rapid population growth. One of the primary land uses is agriculture, primarily for food production (Wang and Li, 2021). The presence of arable land plays a vital role in food production. Expanding the amount of agricultural land results in higher food output, which in turn bolsters food security. Global land use has drastically changed due to the growing need for agricultural products (Costantini, 2015). The preservation of agricultural land is vital for food security. However, there is a significant threat of this land being repurposed for non-agricultural activities. The earth's surface continues to experience land use and cover changes due to the intricate interactions between environmental and socioeconomic factors and the effects of rapid population growth (Estacio *et al.,* 2023; Foyezur *et al.,* 2021). The transformation of agricultural land has repercussions on the physical environment and the social and economic realities of the population, impacting them in both direct and indirect manners (Zhang *et al.,* 2023). The social repercussions that arise include population alterations, migration, lifestyle shifts, traditions, and criminality. The international economic consequences that result encompass shifts in income distribution, rising unemployment in rural areas, and threats to food security (Tufa and Megento, 2022; McKee and Beingessner, 2024). Land use changes are influenced by many factors, including nature (Adebayo *et al.,* 2019), socioeconomic conditions, population, industry, trade, technology, policy development, population growth, accessibility, facilities and infrastructure (Widiastuti and Sudrajat, 2023), urbanization (Dangulla *et al.,* 2020), and transportation infrastructure (Otuoze *et al.,* 2020; Sukri *et al.,* 2022a). Climate change is a significant natural factor that affects food production. It leads to an increase in the frequency of droughts, floods, and heat waves, which in turn disrupts agricultural productivity (Jiménez-Bedoy *et al.*, 2024). Temperature and rainfall patterns affect crop yields, soil quality, and water availability, reducing yields. Warmer temperatures and weather patterns can also increase pests and diseases, further threatening food crop production (Kumar *et al.,* 2021; Saleem *et al.,* 2024; Vogel and Meyer, 2017). Modifications in land use or cover patterns can impact other ecosystems negatively or positively, given that a large number of individuals depend on agriculture and natural resources for their livelihoods. Therefore, environmental and agricultural sectors are considered providers of people's basic needs (Kanianska, 2016). Development is one of the main reasons for land use changes (Liu, 2018). While development brings numerous advantages, it simultaneously increases built-up areas, reduces agricultural land availability, and leads to environmental degradation (Liu *et al.,* 2020). The situation in Special Region of Yogyakarta is no exception. Approximately 150 ha of agricultural land in the Special Region of Yogyakarta has undergone annual modifications in their intended use (Pangaribowo and Rusiana, 2024) because the region is experiencing massive development. Notably, the construction of transportation networks, airport facilities, housing units, and other public services is being prioritized to bolster tourism initiatives and foster regional development (Rijanta *et al.,* 2019). This infrastructure encourages residential and commercial activities (Liu and Su, 2021) and drives the growth of built-up regions. Consequently, it is difficult to pursue development without acknowledging the vital role that agriculture plays in sustaining itself (Lopes *et al.,* 2020). Given that agricultural food productivity is crucial in achieving food security, the land carrying capacity and variations in land usage have become interesting research topics. Changes in land usage are essential when addressing issues about food security. Food security has defined human history. By 2050 or 2060, the global population will reach approximately 9 billion. It is anticipated that food demand will increase twofold in the 21st century, leading to greater challenges regarding land utilization, water resources, and nutritional adequacy (Lone and Mayer, 2019). However, the amount of available agricultural land shows a decreasing trend due to shifting land uses, leading to reduced food production (Kumar *et al.,* 2021 ; Wang *et al.,* 2018) and carrying capacity and causing food insecurity (Yikii *et al.,* 2017). Food insecurity persists throughout the world, particularly in emerging nations. Therefore, food security remains a top priority on the global development agenda (Moreno *et al.,* 2021 ; United Nation, 2015). Ending hunger and achieving food security is one of the Sustainable Development Goals (SDG 2) (Tutunchi *et al.,* 2020). Food security results from the efficient

operation of food systems (Leroy *et al.,* 2015). A well-functioning food system significantly influences the four key aspects of food security: stability, availability, access, and utilization. The concept of food availability pertains to the community's ability to secure an adequate supply of food (Schneckenreither *et al.*, 2015). Therefore, a region's ability to produce food does not guarantee its food security. In addition, a region with sufficient food availability does not necessarily mean it is invulnerable to food insecurity. The Geographic Information System allows for the examination of land use alterations over wide-ranging spatial and temporal scales (Elliot *et al.,* 2020). This technology can also be utilized in developing simulation models that employ the cellular automata (CA) technique to forecast land use changes (Muhammad *et al.,* 2022; Islam *et al.,* 2018) and can be integrated with other methods, such as artificial neural networks (ANNs) (Sukri *et al.,* 2022a; Basir *et al.,* 2021; Qian *et al.,* 2020). The cellular automata and artificial neural networks (CA-ANN) model is a simple, flexible (Guo *et al.,* 2020), and fast prediction tool for land use changes (Liang *et al.,* 2020). Policymakers must adopt appropriate and successful planning to manage land sustainably (Sfa and Nemiche, 2019) so that the optimization of land resources will be guided by the objectives and guidance of regional development (Muta'ali, 2015). The objective of this study is to identify shifts in land use and to carry out simulations that predict future land use changes within the Special Region of Yogyakarta, along with evaluating the implications for the region's agricultural land carrying capacity and food security. The study applies a comprehensive approach by considering the spatial distribution changes in agricultural land and their impacts on food security and land-carrying capacity. By adopting this all-encompassing perspective, the study's contribution to grasping the complex interactions involved in land use change is notably strengthened. This study has been carried out in Special Region of Yogyakarta, Indonesia in 2023.

MATERIALS AND METHODS

Policymakers must adopt appropriate and successful planning to manage land sustainably (Sfa and Nemiche, 2019) so that the optimization of land resources will be guided by the objectives and guidance of regional development (Muta'ali, 2015). This study aims to detect land use changes

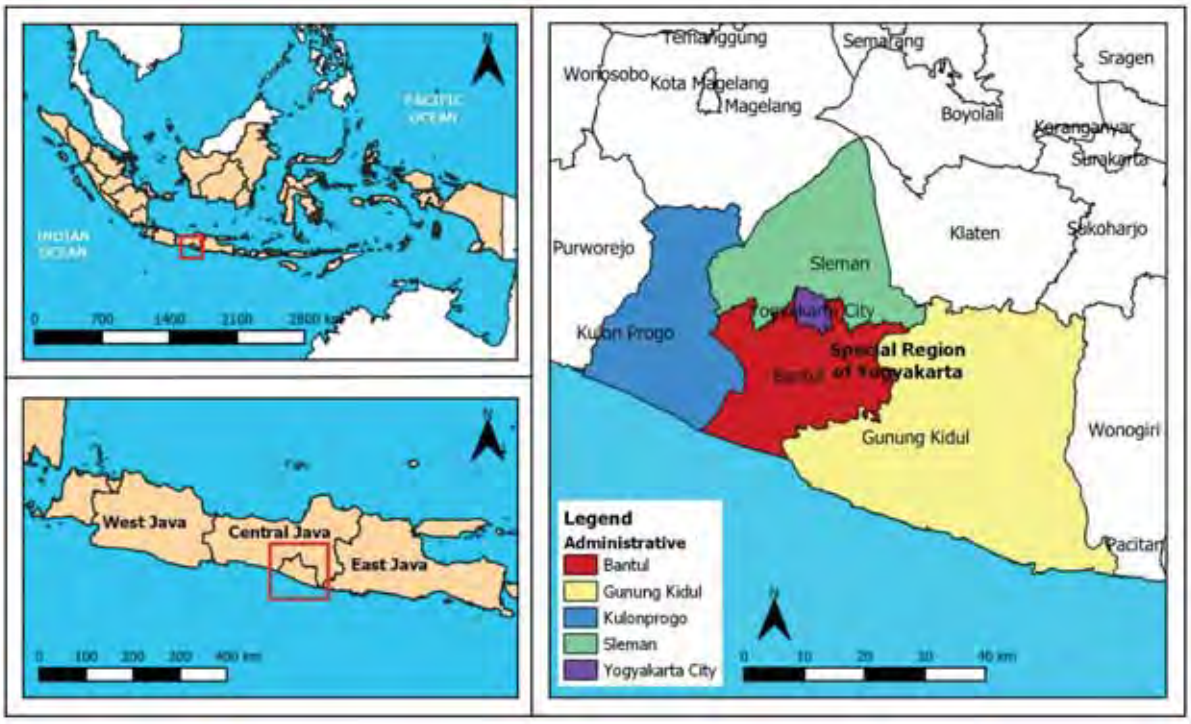


Fig. 1: Geographical location of the study area in special region of Yogyakarta, Indonesia

and performs simulations to predict future land use changes in the Special Region of Yogyakarta and their impact on the region's agricultural land carrying capacity and food security. This study utilizes an integrated approach to analyze the changes in the spatial distribution of agricultural land and their implications for food security and the capacity of the land to sustain agricultural activities. This holistic approach enhances the study's contribution to understanding the complex dynamics of land use change.

Methods

A spatial modeling approach known as cellular automata was applied to anticipate shifts in agricultural land use, leveraging a grid of dimensional cells that engage with one another locally and simultaneously. Each cell holds a state at a given time (t), which can change (T1, T2, etc) by transition rules based on its current state and neighborhood effect. The neighborhood, comprising adjacent cells influencing the central cell, can be Von Neumann's (four neighbors) or Moore's (eight neighbors, including diagonals), with influence decreasing with distance from the central cell based on a specified rank J (number of layers) (Sukri *et al.,* 2022b). Fig. 2 displays this model.

CA can be combined with other methods, one of which is Artificial Neural Network. The integrated CA-ANN model was accessed through computers and quantum geographic information system (QGIS) spatial data processing software. Maps depicting land use and cover were employed as input data or model parameters. Essential components, including transition rules, neighborhood characteristics, transition probability maps, and transition area matrices, underpinned the modeling of agricultural land transformations. The simulation results were validated by map comparison using the Kappa Index of Agreement coefficient, a valid simulation model that is the basis for a prediction map of agricultural land change. The key assumptions made in model include 1) Spatial homogeneity in transition rules. The CA model operates under the assumption that transition rules are uniformly applicable across the entire study area, despite the possibility that urban and rural areas may undergo different transition dynamics. This may cause an inaccurate assessment of changes in particular subregions, leading to either underestimation or overestimation; 2) Neighborhood effects. Limiting influences to immediate neighbors can fail to capture broader-scale spatial interactions. The establishment of Yogyakarta International Airport may have repercussions that extend significantly beyond its neighboring areas, shaping land use across a broader region; 3) Temporal consistency. Predictions based on stable conditions may fail to anticipate abrupt transition, leading to underestimation of rapid urbanization or overestimating of agriculture land retention during a development surge. The model predicting land use change is depicted in Fig. 3.

Fig. 3 show the methodology by integrating CA-ANN to predict land use changes, this model aligns with global best practices combining spatial and functional modeling for enhances accuracy. The use of the Kappa Index and sensitivity analyses ensure robust validation, while agricultural carrying capacity and food security assessment adopt widely recognized frameworks, including Odum's methods and the food security and vulnarebility atlas (FSVA).

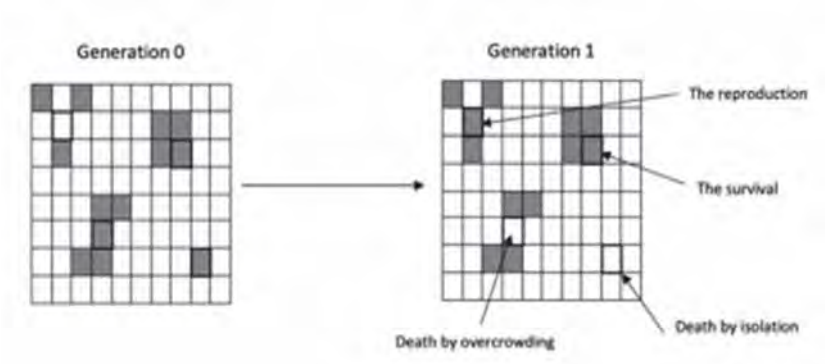


Fig. 2: Transition rules model of cellular automata (Sfa and Nemiche, 2019)

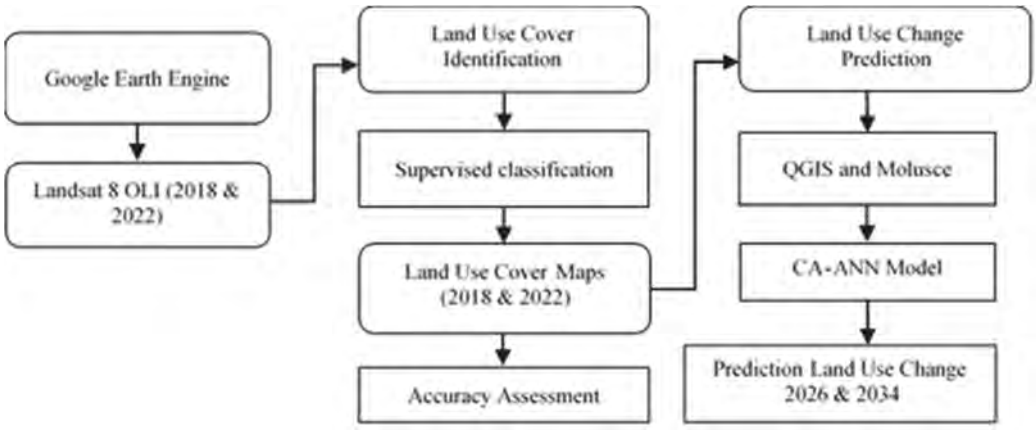


Fig. 3: Prediction of land use changes using the combined cellular automata and artificial neural network

By combining localized nutritional needs with scalable techniques, this thorough approach offers consistent understanding of spatial dynamics and food security. It is adaptability and policy relevance make it a valuable tool for addressing global and regional sustainability challenges.

Carrying capacity of agricultural land

The carrying capacity of agricultural land was used to calculate the availability of wetland agricultural land (supply) to support the population's food needs (demand). The concept of demand was established as the basic physical necessities for food production, whereas availability was characterized by the amount of agricultural land employed by the population. The land carrying capacity refers to agricultural land productivity, namely, the ability to meet or support the minimum physical needs of each resident. Odum, Howard, and Issard developed the following analysis method, using Eq. 1 (Food Security Council, 2015; Food Security Agency, 2020):

$$CCA = \frac{Ha / Po}{MPN / Pr} \quad (1)$$

Where, MPN is the minimum physical needs in kilogram per capita per year (kg/capita/y), HA is the harvested area in ha, Po is the total population (people), and Pr is the rice productivity as kilogram per hectare (kg/ha). The daily calorie requirement for each person was the basis for the MPN. As part of Indonesia, the Special Region of Yogyakarta has a strong cultural and historical relationship with rice consumption, so daily calorie requirements are based on rice consumption. Although rice is not the exclusive provider of calories within the dietary framework, it continues to be an important element of daily calorie intake in Yogyakarta. Therefore, in order to examine the carrying capacity of agricultural land within the research area, it is important to take into account the percentage of calories sourced from rice as opposed to other food items. In the study location, the MPN is 2600 calories per person per day (265 kg of rice per person per year). In this study, predictions of land use changes have not taken into account environmental issues, including soil degradation, water availability, and climate change. The thresholds for agricultural land carrying capacity were determined based on a classification aligning with the FSVA, categorizing regions as ideal (>1), self-sufficient (=1), or insufficient (<1). These thresholds were calculated using parameters such as harvested area, population, and crop productivity, customized to align with the dietary patterns of the study area. These results are particularly sensitive to adjustments in the thresholds, since small variations in population, productivity, or land availability can lead to a reclassification of regions into different categories.

Food security

The obtained food security parameters for food insecurity were converted into an index with a scale of 0 to 1. The processed data were reformulated into index functions to ensure that all food security

parameter values are confined to a consistent range, specifically from 0 to 1. The parameter indices for food security were calculated using Eq. 2 (Food Security Council, 2015):

$$Indeks\ X_{ij} = \frac{X_{ij} - X_{i\,min}}{X_{i\,max} - X_{i\,min}} \quad (2)$$

Where, Xij is the indicator's jth value, Xi min denotes its minimum value, and Xi max denotes its maximum value. The calculated food security indices were then classified into six classes according to FSVA. The methodology used in this study has been adjusted to the characteristics of the research location, namely the Special Region of Yogyakarta. For example, the food security indicator used in this study uses FSVA. While globally, indexes such as global food security index (GFSI), rice bowl index (RBI), and global hunger index (GHI) are more widely used. FSVA is employed due to its capacity to analyze smaller geographic areas, such as Provinces and Regencies. In this study, the FSVA is a thematic map that depicts a geographical visualization of areas vulnerable to food insecurity. FSVA is dedicated to supplying accurate, detailed, and well-structured food security data to aid in the prevention and management of food and nutrition insecurity. This information is intended to inform and guide decision-makers in the formulation of programs, policies, and implementation of interventions at the central and national levels area. FSVA is prepared based on three aspects of food security: availability, affordability/access, and food utilization. The Provincial FSVA analyzes areas at the sub-district level (Mota *et al*., 2019). Of the 14 indicators used in the 2005 Food Index Analysis (FIA), 13 have been selected and used in the FSVA after going through a review process by the FSVA steering committee (Steering Committee) and implementing team (Technical Working Group), which has been formed to update the FSVA. As data concerning the infant mortality rate (IMR) is not available, this particular indicator has been excluded from the FSVA assessment. FSVA was developed using nine chronic food insecurity indicators and four temporary/transient food insecurity indicators. Mapping at the provincial level uses these 13 indicators, consisting of 9 indicators for mapping areas of chronic food security and vulnerability and four indicators (vulnerability aspects) for mapping transient food insecurity (Pujiati *et al.,* 2020). This study incorporated six indicators that stem from three key areas: 1) food availability, including the ratio of normative per capita consumption to net availability of cereals; 2) access to food, including the percentage of the population living below the poverty line without electricity, and without access to clean water; and 3) The assessment of food utilization encompasses the ratio of health personnel to the population, taking into account population density, as well as the percentage of children whose body weight falls below the standard, indicating stunting. Not all indicators were used in this study based on their representation of the three pillars of food security, the level of sensitivity in measuring the food and nutrition security situation, and the availability of routinely collected data covering all sub-district areas in the study (Zhang and Tian, 2024). The interplay between the various indicators employed in the FSVA and food security is significant and detailed in the subsequent item: 1) Food availability aspect. This aspect is indicated by food production in the research area, particularly cereals like rice. The quantity of food production indicates the region's ability to meet the food adequacy level of the population. 2) Aspects of access to food. This dimension addresses the ability of households to access enough food via various strategies, including their own agricultural output, stored food, purchases, bartering, gifts, loans, and assistance programs. Even if food availability in an area is sufficient, not all households may have adequate access to food in terms of quantity and diversity through these mechanisms. a) Percentage below the poverty line. This indicator illustrates the monthly expenditure in rupiah per capita necessary to achieve the minimum standards for both food and non-food consumption. Individuals living below the poverty line lack sufficient purchasing power to meet their basic needs, leading to food insecurity. b) Percentage of households that do not have access to electricity: The availability of electricity in an area enhances access to work opportunities, indicating a region's or household's welfare, which impacts food security conditions. c) Percentage of households without access to clean water: This indicator represents the percentage of households without access to clean drinking water. Access to clean water is essential for ensuring food security, as

contaminated water can lead to higher rates of illness, diminish the body's capacity to absorb nutrients, and negatively impact overall nutritional health. 3) Food utilization aspect. a) Ratio of population per health personnel to population density level. This indicator measures the suitability between the availability of health workers and the number of patients. This ratio affects the level of food vulnerability. b) Percentage of children's body weight below standard (Stunting): This indicator illustrates the nutritional health of children younger than five years, highlighting their capacity for food absorption. Factors influencing this status include household food security, maternal nutritional and health status, maternal education, parenting patterns, access to clean water, and timely health services. Data sources for calculating Food Security are presented in Table 1.

The classes, categories, and levels of food security indices are described in Table 2.

RESULTS AND DISCUSSION

Land use change

Maps for 2018 and 2022 were produced by identifying the land use in the Special Region of Yogyakarta, and maps for 2026 and 2034 were drawn by projecting changes in land use cover (Fig. 4). Simulations using the land use maps for 2018 and 2022 were carried out to predict the future changes in land use in this region (2026 and 2034). Each land use area, as determined by the picture categorization results, is shown in Table 3. The classification findings for 2018 and 2022 indicate an average accuracy rating of 85 percent (%) based on crosschecks in the field. This result indicates that the categorization map is classified as excellent and is appropriate for simulations predicting land use change. Key components utilized in the simulation consist of transportation routes, demographic density, and pre-existing urbanized land.

Fig. 4 and Table 3 provide a comprehensive overview of land use change in Yogyakarta, Indonesia, over four years, with projections up to 2034. The data highlights significant changes in land use patterns, including fluctuations in dryland farming, bodies of water, constructed areas, ponds, shrublands, open lands, and rice fields across these regions. In 2018, as

Table 1: FSVA indicators and data sources

No.	Indicators	Data sources
1	The ratio of normative per capita consumption to net availability of cereals	DIY Provincial Agriculture Service Central Bureau of Statistics
2	Percentage of the population living below the poverty line	National Socioeconomic Survey DIY Provincial Social Service DIY Provincial Regional Planning Development Agency
3	Percentage of the population without electricity	National Socioeconomic Survey, Central Bureau of Statistic Yogyakarta Provincial Department of Energy and Mineral Resources DIY Provincial Social Service
4	Percentage of population without access to clean water	National Socioeconomic Survey, Central Bureau of Statistic DIY Provincial Regional Planning Development Agency DIY Provincial Health Service
5	The ratio of population per health worker to population density	Profile of Health Workers, DIY Provincial Health Service
6	Percentage of children's body weight below standard (stunting)	Nutritional Status Data, DIY Provincial Health Service

Table 2: Food security classes and categories (Food Security Agency, 2020)

Classes	Regency	City	Category
1	≤ 41.52	≤ 28.84	Highly food insecure
2	> 41.52 - 51.42	> 28.84 - 41.44	Food Insecurity
3	> 51.42 - 59.58	> 41.44 - 51.29	Somewhat food insecure
4	> 59.58 - 67.75	> 51.29 - 61.13	Sufficiently food safe
5	> 67.75 - 75.68	> 61.13 - 70.64	Food security
6	> 75.68	> 70.64	Highly food security

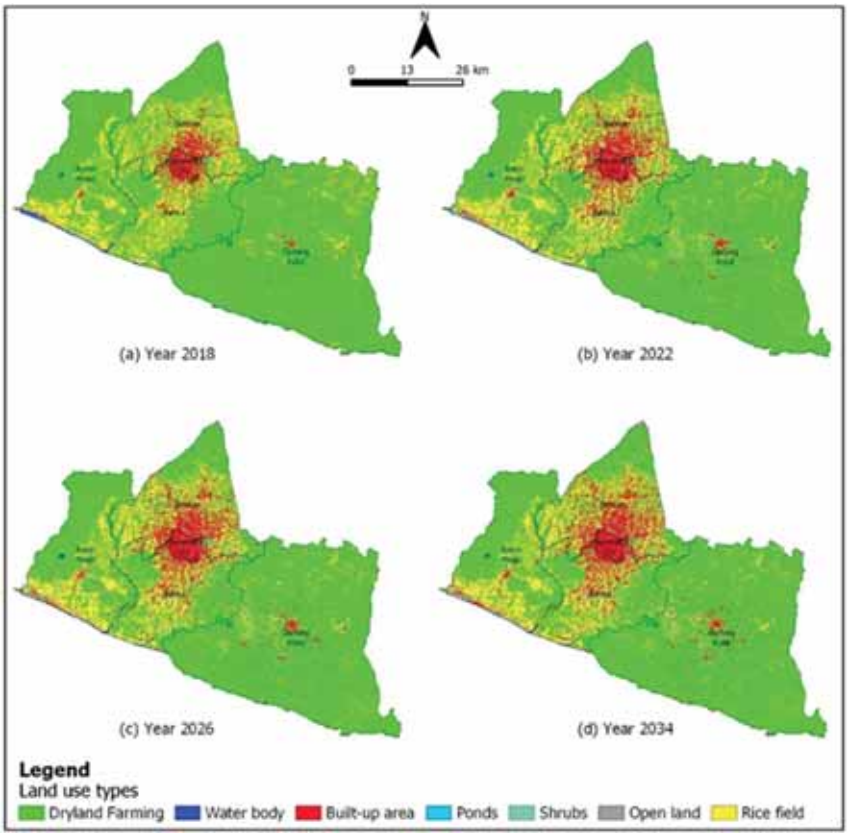


Fig. 4: Land use change map for the special region of Yogyakarta

depicted in Fig. 4a, the predominant land use was dry land agriculture, covering 223,397.97 ha representing 70.36% of the total area. This was followed by rice fields at 65,688.15 hectares (ha) (20.69%), built-up land at 19,258.34 ha (6.07%), open land at 3,663.01 ha (1.15%), water bodies at 3,013.16 ha (0.95%), grass and shrubs at 1,895 ha (0.60%), and ponds at 607.59 ha (1.19%). Changes were observed for all these land uses until 2022 (Fig. 4b): some increased, and some decreased. The highest increase in land use cover was recorded for grass/shrubs at 19,711 ha (6.21%), followed by buildup land and rice fields at 12,421 (3.91%) and 348 ha (0.11%), respectively. The most significant increase in grass/shrubs occurred in Gunungkidul, covering 9,035 ha. A significant portion of the Gunungkidul area is dominated by vegetation, attributed to human influence, natural transitions, or seral stages in ecological development (Mirzabaev *et al.,* 2023). The largest increase in built-up land occurred in Sleman Regency, covering an area of 4,931 ha, and the increase in rice fields was recorded in Kulon Progo Regency at 981 ha. The most significant reduction in land use/cover occurred for dry agricultural land at 31,235 ha (9.84%), followed by open land, water bodies, and ponds at 661 (0.21%), 438 (0.14%), and 147 ha (0.05%), respectively. Gunungkidul Regency experienced the most extensive conversion of dry agricultural land, totaling 12,471 ha. The open land occurred in Sleman Regency at 677 ha, the ponds in Kulon Progo Regency at 107 ha, and the water bodies in Kulon Progo Regency at 195 ha. According to Pham (2015) underlying forces, proximal causes, and predisposing environmental factors are responsible for the increased built-up land area. At the study location, Yogyakarta City is influenced by its underlying strength as the province's center. Concurrently, the neighboring areas are impacted by their nearness to the provincial capital, with Sleman Regency being particularly affected. Moreover, the forces of growth and a high population density are

Table 3: Land use changes in Yogyakarta's special region

No.	Region	Land use	Classification		Prediction	
			2018 (ha)	2022 (ha)	2026 (ha)	2034 (ha)
1	Bantul	Dryland farming	28,538.43	21,737.68	21,834.79	21,229.66
		Body of water	751.62	688.67	640.63	669.62
		Constructed area	4,667.25	7,991.44	8,566.04	9,391.22
		Ponds	108.41	121.61	118.89	118.42
		Shrubs	250.58	3,914.20	3,527.74	3,712.00
		Open land	764.99	311.17	276.46	332.83
		Rice Field	16,474.46	16,790.97	16,591.19	16,101.99
2	Gunungkidul	Dryland farming	127,868.99	115,397.42	117,582.98	114,675.54
		Body of water	321.00	211.70	225.91	241.41
		Constructed area	3,313.93	6,190.05	6,297.36	7,413.45
		Ponds	138.76	85.48	80.51	82.81
		Shrubs	1,188.38	10,223.96	9,447.43	9,883.98
		Open land	724.02	1,520.77	1,245.96	1,518.02
		Rice field	13,804.15	13,729.85	12,479.08	13,544.02
3	Yogyakarta City	Dryland farming	197.59	52.35	50.15	52.08
		Body of water	21.15	3.00	2.97	3.06
		Constructed area	2,625.02	2,761.03	2,838.23	2,760.11
		Shrubs	6.19	133.46	112.97	134.40
		Open land	113.16	207.84	164.51	207.64
		Rice field	327.39	132.82	121.67	133.21
4	Kulon Progo	Dryland farming	38,422.43	34,207.66	34,527.40	34,007.16
		Body of water	1,379.37	1,183.80	1,130.26	1,159.75
		Constructed area	1,175.12	2,329.06	2,451.78	3,070.45
		Ponds	360.42	253.31	245.59	244.37
		Shrubs	154.01	2,957.17	2,738.06	2,835.22
		Open land	576.94	155.72	176.76	267.30
		Rice field	15,816.04	16,797.61	16,614.48	16,300.08
5	Sleman	Dryland farming	28,370.53	20,767.69	20,533.86	19,871.11
		Body of water	540.02	487.52	438.86	453.03
		Constructed area	7,477.02	12,408.63	13,661.91	15,045.28
		Shrubs	295.84	4,378.08	3,839.64	3,986.19
		Open land	1,482.90	805.50	720.07	815.20
		Rice field	19,266.11	18,585.00	18,238.08	17,261.61
	Special region of Yogyakarta		317,522.22	317,522.22	317,522.22	317,522.22

the primary contributors to the substantial alterations in land use occurring in Sleman Regency. In Kulon Progo Regency, apart from the increasing population, the construction of the new Yogyakarta International Airport has triggered an increase in built-up land in this area. This result is in line with the study of (Sukri *et al.*, 2022a), who states that population growth and transportation infrastructure development are triggers for the increase in built-up land. Consequently, converting agricultural land to built-up areas becomes a notable consequence of these dynamics, echoing similar trends observed in Suzhou, China (Kurowska *et al.*, 2020). From a spatial perspective, the changes in agricultural land shown in image classification (Fig. 4a and 4b) reveal that Sleman Regency had the most significant decrease in agricultural land and the largest increase in constructed area. This result demonstrates that the growth in developed land significantly impacts the decrease of agricultural land. This result is in line with the report by Kurowska *et al,* (2020), who state that the loss of agricultural land and greenery due to conversion to other uses is a natural consequence of urbanization and built-up land development. In the coastal areas of Bangladesh, the high population density is prompting the conversion of land into urban developments (Pham *et al.,* 2015). Furthermore, population growth causes the conversion of agricultural land into populated regions because socioeconomic amenities and dwelling places are necessities for everyone

(Kurowska *et al.,* 2020), and agricultural land is a land use that is easy to convert and vulnerable to conversion. It is crucial to conduct a detailed evaluation of LUC to understand how environmental changes affect agricultural production, to adopt effective land use policies and management practices, and to secure sustainable land use and management (Parven *et al.,* 2022). Land conversion in Bahawalnagar District, Punjab, Pakistan, over a period of 30 years has resulted in a reduction in land area of about 30%, which is a major driver of environmental change (Raza, *et al.*, 2022). A notable correlation exists between the indicators utilized in FSVA mapping and changes in agricultural land use. As a region's economy develops, there is a trend of decreasing agricultural land area due to the conversion of rice fields to other uses. This shift in land use poses a serious threat to the region's food security sustainability (Sukri *et al.*, 2022b). Population growth is the main catalyst for alterations in agricultural land use, leading to a greater demand for residential land (Khasanah and Gunanto, 2024). This trend indirectly impacts impoverished individuals, who may struggle to find adequate housing. The poverty status of the population affects their ability to afford food, thereby influencing food security. The projected changes in agricultural land and built-up land in the Special Region of Yogyakarta (Figs. 4c and 4d) highlight the need for proactive policy measures to manage land use changes effectively. The considerable rise in constructed land, particularly in the southern and northern sectors, signifies a movement towards urbanization and the enhancement of infrastructure. To address this trend, the government should focus on sustainable urban planning and land use management to minimize the loss of agricultural land. Strategies to maintain a balance in agricultural land utilization should encompass actions that prevent the conversion of agricultural regions into urbanized spaces. This can be achieved through zoning regulations, land use planning that prioritizes agricultural areas, and incentives for agricultural production (Sukri *et al.*, 2022a). Additionally, the government can promote alternative land use practices, such as vertical farming or agroforestry, to increase agricultural productivity without expanding land area. The experience in Kulon Progo Regency, where the acreage of rice fields increased despite conversion to built-up land, underscores the importance of strategic planning and policy implementation. The sustainable agricultural land and food program in Indonesia, designed to offer extra land to offset the conversion of rice fields, stands as an exemplary model for other regions dealing with similar challenges (Sukri *et al.*, 2023). Policy interventions should replicate successful strategies from such programs while considering the local context and the need to ensure sustainable land use and food security in the Special Region of Yogyakarta and beyond. Key elements driving the shift of agricultural land to urban development are the increasing urban population, particularly evident in Yogyakarta, where a substantial student community leads to a yearly rise in temporary residents. Research in Niamey (Nasser and Adam, 2024) indicates that urbanization and population increase have led to a substantial reduction in agricultural land, with developed areas expanding from 1,352 ha to 11,596 ha between 1975 and 2020. The subsequent driver is economic development and income growth, as observed in the United States, where national income substantially facilitates the transformation of agricultural and forest land into urban land (Alijani *et al.,* 2024). Infrastructure development serves as an additional catalyst for the conversion of agricultural land. In West Java, Indonesia, proximity to toll gates significantly influences the conversion of agricultural land to urban areas (Gandharum *et al.,* 2024). The governance frameworks and policies enacted by involved parties are essential factors influencing land conversion. The Romanian government's program, deemed inefficient from 1990 to 2005, led to a substantial shift of agricultural land into developed regions (Meyer and Früh-Müller, 2020). Furthermore, sensitivity analyses were conducted to highlight the reliability and limitations of the CA-ANN model. The results are shown in Fig. 5.

Fig. 5 show the sensitivity analysis of land use change in the Special Region of Yogyakarta using the CA-ANN model. The model adeptly captures trends, notably the gradual rise in constructed spaces propelled by urbanization and the robust preservation of rice fields, illustrating its effectiveness in simulating stable categories of land use. However, notable limitation emerge in dynamic categories like ponds and shrubs, which exhibit significant fluctuations that could indicate sensitivity to parameter variations in transition probabilities.

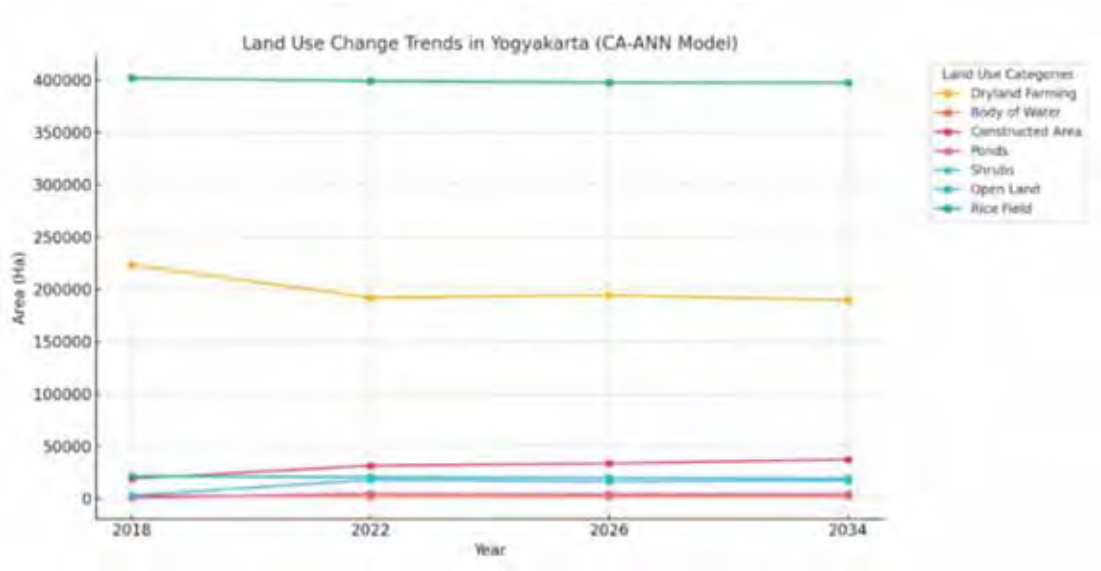


Fig. 5: Sensitivity analyses of CA-ANN Model

Carrying capacity of agricultural land

The carrying capacity of regions where most people work in agriculture can be computed using minimum physical requirements and agricultural land production. This analysis of agricultural carrying capacity sought to evaluate if the yearly rise in population can be sustained by corresponding increases in productivity and the capacity of agriculture to support that growth. In particular, the relationship among population size, harvested area, and rice food production was examined. These three factors for the Special Region of Yogyakarta Province in 2018, 2019, 2020, 2021, and 2022 are presented in Table 4.

Table 4 shows that Kulon Progo Regency had the most significant average rice production in 2018 at 6,055 kg/ha, and Gunungkidul Regency had the lowest in 2019 at 4,060 kg/ha. The expansion of land area in each district or city does not consistently correlate with an annual rise in rice production. This result agrees with Khasanah and Gunanto's (2024), showing that the harvested area did not significantly affect food crop production, especially horticulture. The year 2020 marked a downturn in rice production across nearly all research areas, but this trend was reversed with an increase in the years that followed. This phenomenon is closely linked to the global impact of the Coronavirus-2019 (COVID-19) pandemic. The productivity of rice fields in Yogyakarta City tended to increase yearly, even though the area of rice-harvested land continued to decline from 2018 to 2022. In contrast to other districts/cities, Bantul Regency experienced a decline in productivity in 2022. Land conversion in Bantul Regency impacts its decreasing rice production and productivity. The rapid economic increase and the number of industries have converted rice land in Bantul Regency into built-up areas, thus affecting its rice productivity. Moreover, the population, harvested land area, and productivity across each research area were examined to evaluate the carrying capacity of the agricultural land (CCA), as detailed in Table 5.

Table 5 shows that the carrying capacity of the agricultural land in the Special Region of Yogyakarta between 2018 and 2022 ranged from 0.0026 to 1.034. Gunungkidul Regency had the highest agricultural land carrying capacity in 2018–2021 because its food availability is higher than in other regions where the harvest area is high and the population is moderate. This finding is supported by the study of Iguna *et al.* (2022), who state that almost all areas in the Gunungkidul district are optimal and capable of meeting food needs. In contrast, the reduced carrying capacity of various areas results from insufficient food supply despite a significant demand for food. Food availability is low due to the small harvested

Table 4: Relationship between population, harvest area, and rice production in the Special Region of Yogyakarta 2018-2022

Region	Year	Total population (people)	Harvested area (ha)	Rice production (kg/ha)
Kulon Progo	2018	426,767	13,332.00	6,055
	2019	432,058	16,111.37	5,834
	2020	437,373	15,881.00	5,238
	2021	442,724	16,309.77	5,737
	2022	448,131	20,329.07	6,042
Bantul	2018	1,009,171	19,762.00	5,735
	2019	1,022,788	21,207.93	5,761
	2020	1,036,489	21,654.66	5,660
	2021	1,050,308	24,670.88	5,753
	2022	1,064,286	24,124.19	5,620
Gunungkidul	2018	740,181	31,300.00	5,368
	2019	749,229	49,671.44	4,060
	2020	758,316	49,157.13	4,189
	2021	767,464	41,993.90	4,701
	2022	776,705	43,690.19	4,617
Sleman	2018	1,214,346	27,615.00	4,903
	2019	1,231,246	24,465.85	4,723
	2020	1,248,258	23,842.32	4,684
	2021	1,265,429	24,525.71	5,039
	2022	1,282,804	23,996.29	5,023
Yogyakarta City	2018	427,801	26.00	5,423
	2019	423,267	20.77	5,182
	2020	438,761	12.98	5,271
	2021	444,295	5.90	5,288
	2022	449,890	8.26	5,500

Table 5: Carrying capacity of Yogyakarta's special region's agricultural land

Region	Year	Supply	Demand	CCA	Category
Kulon Progo	2018	0,031	0,044	0,71	
	2019	0,037	0,045	0,82	
	2020	0,036	0,051	0,72	
	2021	0,037	0,046	0,80	
Bantul	2018	0,020	0,046	0,42	
	2019	0,021	0,046	0,45	
	2020	0,021	0,047	0,45	
	2021	0,023	0,046	0,51	
	2022	0,023	0,047	0,48	
Gunungkidul	2018	0,042	0,049	0,86	
	2021	0,055	0,056	0,97	Class III
	2022	0,056	0,057	0,98	
Sleman	2018	0,023	0,054	0,42	
	2019	0,020	0,056	0,35	
	2020	0,019	0,057	0,34	
	2021	0,019	0,053	0,37	
	2022	0,019	0,053	0,35	
Yogyakarta City	2018	0	0,049	0	
	2019	0	0,051	0	
	2020	0	0,05	0	
	2021	0	0,05	0	
	2022	0	0,048	0	
Kulon Progo	2022	0,045	0,044	1,03	
Gunungkidul	2019	0,066	0,065	1,02	Class II
	2020	0,065	0,063	1,02	

area and agricultural land conversion. The reduction in agricultural land impacts the decline in its carrying capacity (Mijena *et al.,* 2022). The indicators utilized in FSVA mapping are fundamentally associated with the capacity of agricultural land to sustain production and ensure food security. In 2022, Kulon Progo Regency had the highest agricultural carrying capacity, followed by Gunungkidul, with values of 1.03 and 0.98, respectively. Kulon Progo Regency experienced a significant increase in the harvested land area, thus increasing its carrying capacityThis finding aligns with the study conducted by Sukri *et al.* (2023), which indicates that changes in agricultural land use impact the food production capacity of these areas by affecting both the extent of harvested land and the productivity of rice cultivation. Raising the productivity of agricultural land and producing staple foods can help control the four aspects of food security: availability, access, use, quality, and stability; therefore, the level of agricultural carrying capacity is crucial (Rozaki, 2020; Sukri, 2022a). The government and all parties involved in agriculture must focus on maintaining the sustainability of agricultural land and develop agricultural systems to preserve their carrying capacities (Ashley, 2016). The global agricultural land carrying capacity will affect food security. As a study by Wang (2022) states that the rise in urbanization causes changes in soil quality, water availability, and climate, all of which can affect food crop production. Water resource availability, solar energy potential, and the appropriateness of land for agriculture are critical determinants of agricultural output and the land's ability to sustain farming. The spatiotemporal fluctuations in the carrying capacity of the food agricultural land in the Yogyakarta Special Region are depicted in Fig. 5.

Fig. 6 shows the temporal changes in the carrying capacity of food agricultural land in the Special Region of Yogyakarta in 2018 and 2022. With the sole exception of Gunungkidul Regency, all other regions demonstrated a low agricultural land carrying capacity in 2018. However, in 2022, Kulon Progo Regency's carrying capacity had significantly increased to good levels. This region is distinguished by its extensive range of agricultural goods, which collectively fulfill the agricultural needs of the local population. The land available is greater than what is needed, indicating an excess in carrying capacity. Nonetheless, it remains crucial for the government or other stakeholders to continue developing agriculture in this region to sustain surplus conditions (Iguna *et al.,* 2022), including in urban areas. Ashley (2016) highlights that urban agriculture can enhance agricultural land's carrying capacity, particularly

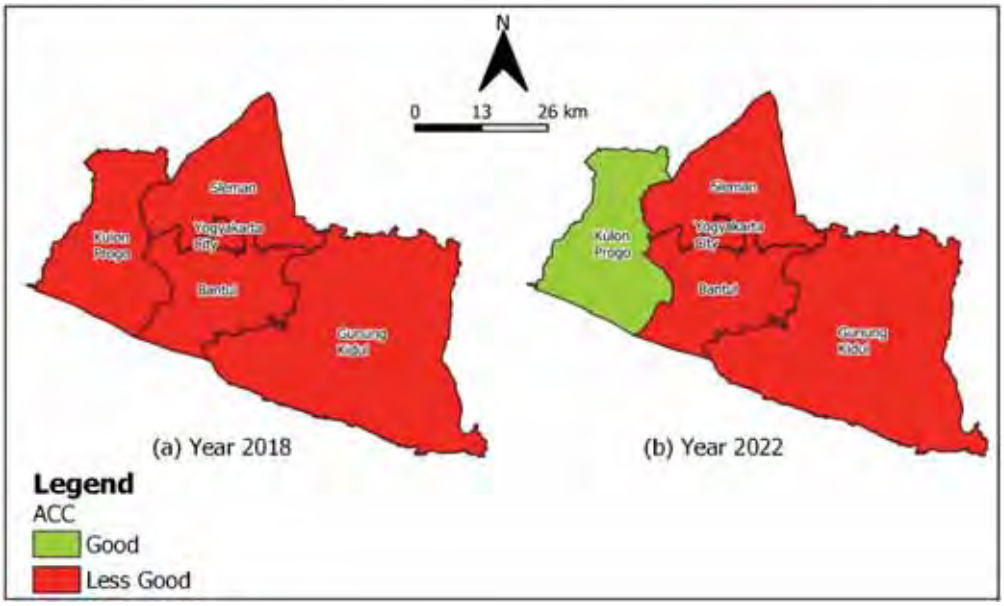


Fig. 6: Variations in the agricultural land's carrying capacity in Yogyakarta's special region

Table 6: Indicators of access to food for the population of the special region Of Yogyakarta

Region	Percentage of population living below the poverty line		Percentage of population without electricity		Percentage of population without access to clean water	
	2018	2022	2018	2022	2018	2022
Bantul	13.43	12.27	0	0	44.81	21.48
Gunungkidul	17.12	15.86	0.15	0	40.80	45.34
Yogyakarta City	6.98	6.62	0	0	31.46	19.98
Kulon Progo	18.30	16.39	0.65	0	42.58	20.11
Sleman	7.65	7.74	0	0	43.81	21.38

in developing countries. Various measures can be employed to enhance agricultural output to attain food security. These techniques include leveraging digital technologies like Big Data, AI, IoT, and robotics to promote precision agriculture. By employing data-driven techniques for crop monitoring and management, these methods aim to enhance agricultural yields and improve resource efficiency (Singh *et al.*, 2020). Moreover, AI and IoT can deliver real-time data regarding soil conditions, weather, and plant health, facilitating the effective use of resources like water and fertilizers (Vinod *et al.*, 2024). Technology can also be utilized in agricultural mechanization. Employing automated machinery, including robotic systems and digital harvesters, streamlines the management of vast agricultural landscapes (Parashar *et al.*, 2024).

Food security

Apart from food availability, the two other essential elements related to food security are food access and individual's use of sufficient food. Access to clean water and electricity are important indicators of a person's access to food. The different facets of food access are outlined in Table 6.

Table 6 shows that in 2018 and 2022, the districts/cities with the lowest percentage of population living on the poverty line were in Yogyakarta City. Consequently, the quality of life for its residents is typically favorable. However, Kulon Progo Regency experienced the highest rate of individuals living in poverty in the years 2018 and 2022. Data from Central Bureau of Statistics (2020) show that almost 329 thousand people (73.33%) of the poor population in the Special Region of Yogyakarta are concentrated in three districts, namely, Kulon Progo, Bantul, and Gunungkidul. The specific topographical and environmental limitations of Kulon Progo Regency pose numerous challenges to the development of its economic capabilities, thereby obstructing progress in reducing poverty (ADCIS, 2022). In this region, families had equal access to electricity in 2018 and 2022. According to the next indicator, namely, the percentage of houses without power, relatively few people needed access to power. This situation can impact its economic activity. This number will rise if the neighborhood has access to electricityboost in economic activity will enable individuals to secure employment opportunities. Major advancements in job availability will improve the living standards of those in Yogyakarta's Special Region. Conversely, Kulon Progo Regency exhibits the largest share of households without electricity access. Regarding livelihoods and food availability, one of the parameters of food security is the population without access to power. Getaneh *et al.*, (2022) found that economic access positively affects household food security. Regarding the indicator of households without clean water, Bantul Regency had the highest percentage in 2018, and Gunungkidul Regency had the highest percentage in 2022. This finding indicates that many homes still face difficulties in obtaining clean water. Clean water is closely related to the quality of food absorbed by the body and is directly proportional to people's nutritional status (Sharma *et al.*, 2021). The improvement of the community's nutritional and nutrient status will lead to increased food security. A standard body weight in toddlers is linked to optimal nutrient absorption. Despite receiving excellent care, toddlers are also affected. Adequate food security measures will contribute to the nutritional well-being of children who are under five years old. The aspects of food utilization are presented in Table 7.

This study further investigated two important elements in the assessment of food security in the Special Region of Yogyakarta: the proportion of underweight children (stunting) and the population ratio of health workers to population density.

Table 7: Indicators of access to food for the population of the special region of Yogyakarta

Region	The ratio of population per health personnel to population density		Percentage of children's body weight below standard (Stunting)	
	2018	2022	2018	2022
Bantul	0.27	0.10	9.75	8.36
Gunungkidul	1.57	53.63	18.47	15.75
Yogyakarta City	0.01	0.01	12.82	12.88
Kulon Progo	0.41	0.24	14.31	10.35
Sleman	0.09	0.05	11.00	6.62

Table 8: Food security index (2018) in the special region of Yogyakarta

Regency/City	Availability	Access	Utilization	Food security index	
				Total	Category
Sleman	25.60	19.61	30.52	75.73	Highly food security
Bantul	25.10	21.38	30.74	77.22	Highly food security
Kulon Progo	19.88	25.17	32.01	77.06	Highly food security
Gunungkidul	20.57	25.63	30.68	76.88	Highly food security
Yogyakarta City	-	29.95	36.39	66.34	Food security

Table 9: Food security index (2022) in the special region of Yogyakarta

Regency/City	Availability	Access	Utilization	Food security index	
				Total	Category
Sleman	25.75	19.4	28.45	73.60	Food security
Bantul	24.97	22.35	28.77	76.09	Highly food security
Kulon Progo	19.76	23.60	28.90	72.26	Food security
Gunungkidul	20.66	25.42	33.22	79.30	Highly food security
Yogyakarta City	-	31.29	40.46	71.75	Highly food security

According to Table 7, Gunungkidul Regency was the subdistrict with the highest population ratio per health worker to population density. Consequently, the number of health staff in the district aligns with the population density. Yogyakarta City had the lowest population-to-health-worker ratio; the city's health-worker population must be increased to support the area's overall population density. Health personnel must be supplied in enormous numbers because Yogyakarta City is quite crowded and has a dense population. The percentage of stunted children's body weight was another food utilization indicator. The highest percentage was observed in Gunungkidul Regency, whereas Bantul Regency in 2018 and Sleman Regency in 2022 reported the lowest percentages. Despite this, both regencies remain capable of supplying nutritious food to their populations. According to Sharma *et al.* (2021), socioeconomic status is an essential determinant of health, nutritional status, mortality, and morbidity. The findings indicate that the economic status in the research area is quite good. Moreover, a toddler's food absorption capability is impacted by their appropriate body weight. The nutritional well-being of toddlers is related to their weight, regardless of the level of care they receive. Food security will be impacted by children under five years old having a sufficient nutritional status (Iqbal and Ali, 2021). Therefore, the food security conditions will also be good. Availability, access, and food utilization are measured to obtain food security scores. The FSI for the research area is presented in Table 8 for 2018 and Table 9 for 2022.

Two districts, namely, Sleman and Kulon Progo, had the best value or score in the resistance or priority five of the 2020 FSVA criteria based on the food security index. Yogyakarta's Special Region received a food security index rating that fell into either the fourth

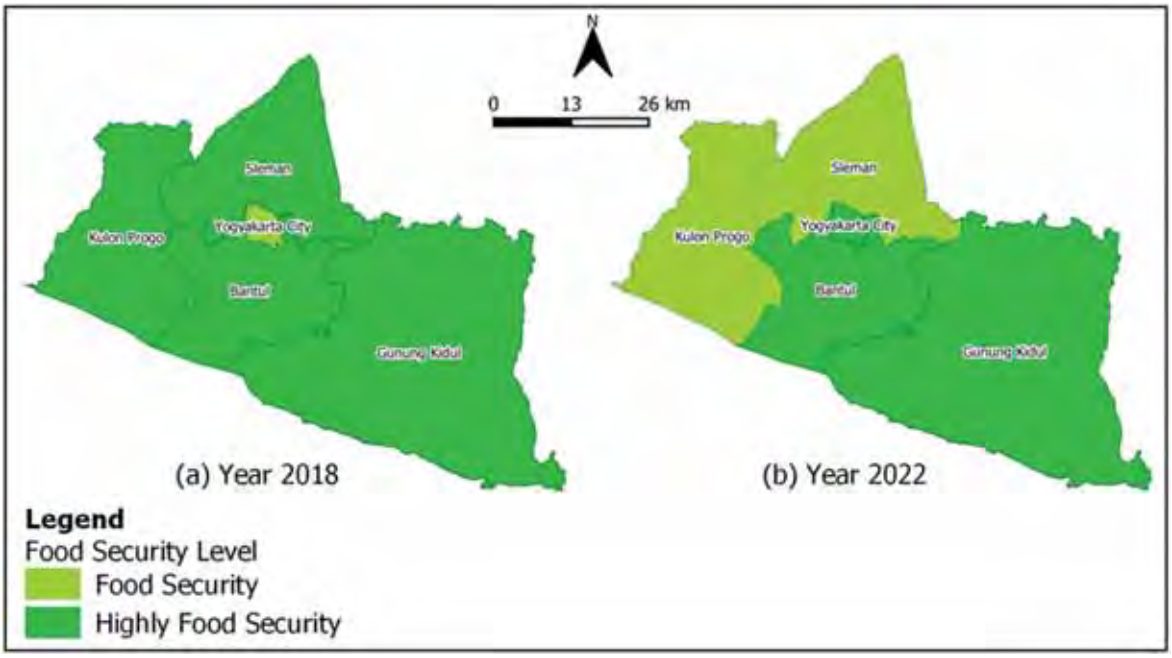


Fig. 7: Food security indeks map of the Special Region of Yogyakarta Province

priority level or the moderately stable classification. Fig. 6 displays spatial variations in food security within the study area.

The spatial distribution of the average food security index for the Special Region of Yogyakarta is represented in Fig. 6. In 2018, most areas in this region had high food security. Yogyakarta City was the only city in 2018 with the lowest food security at 66.34. In 2022, Kulon Progo Regency and Sleman Regency had a lower food security level than the previous year. As reported by Rahmansyah *et al*. (2020), the region of Sleman Regency showed the least average in terms of food availability and access, whereas Kulon Progo Regency recorded the lowest average for food stability and quality. The findings regarding the food security rate in Gunungkidul Regency underscore the importance of prioritizing sustainable agricultural practices and environmental conservation efforts. With its notable food security rate, Gunungkidul stands out as a potential model for other regions that are encountering food security challenges in 2020 (Iguna *et al.,* 2022). The carrying capacity determines how self-sufficient a region can be in food (Fuad *et al.,* 2020). For sustainable food security in the face of a rising population, it is essential to find a harmonious balance between the environmental carrying capacity and the demands of food production (Wang, 2022). Policy implications should focus on enhancing agricultural productivity while preserving natural resources and environmental quality (Boutagayout *et al.,* 2023). This objective can be realized through the implementation of sustainable farming techniques, such as agroecology and conservation agriculture, that foster soil vitality, promote biodiversity, and ensure efficient water conservation (Dönmez *et al.,* 2024). Additionally, policies should encourage the adoption of technologies and practices that improve agricultural efficiency and reduce environmental impact, such as precision agriculture and integrated pest management (Khose *et al.,* 2023). Furthermore, efforts to reduce food vulnerability should include investments in infrastructure (Dönmez *et al.,* 2024), such as irrigation systems and storage facilities, to support agricultural production. Extension services should be strengthened to provide farmers with technical, financial, and managerial assistance (Tigistu and Hegena, 2022). Moreover, policies ought to promote sustainable land use practices while discouraging the transformation of agricultural land for non-agricultural purposes. Governments can contribute to achieving long-term food security and environmental sustainability

goals by prioritizing sustainable agriculture and environmental conservation. The policy strategies implemented in various districts to prevent land degradation, maintain carrying capacity, and increase food security were based on in-depth interviews with stakeholders. The food diversification program was launched by Bantul Regency, while Gunungkidul Regency prioritized infrastructure improvements, digital advancements, and community engagement to reduce land conversion. Kulon Progo Regency implemented a rice field printing program to develop superior varieties, while a draft Regional Regulation strengthened staple food diversification and land conversion regulations. Taniku's digitalization program aimed to increase regional income and suppress land conversion. The Regional Government of Sleman Regency has introduced a Regional Regulation that collaborates with landowners on a digitalization program for agricultural products, as well as incentive schemes designed to curb land conversion and encourage vertical land development. These policies aim to strengthen socialization, increase agricultural product income, and reduce land conversion. The results of the study in the form of strategies and policies can be applied by policy makers such as the Regional Government to create programs that are realized through Regional Regulations, Spatial Planning (RTRW), and Regional Strategic Plans. Local farmers can implement these policies in practice through regulations that facilitate the distribution of fertilizers, the provision of quality plant seeds, and the offering of training in sustainable agricultural practices. To successfully include climate resilience and adaptive agricultural practices into future research on agricultural carrying capacity, it is essential to examine many critical factors. These elements encompass minimizing the effects of climate change (Teklu *et al.,* 2022), wherein climatic resilience enables agricultural systems to endure and recuperate from climate-related disruptions such as droughts, floods, and severe weather events. By adopting conservation agriculture practices, farmers can strengthen their buffering capacity, which helps them to preserve both output and income during challenging circumstances (Affoh *et al.,* 2024). To enhance food security, using smart agricultural methods such as crop rotation, intercropping, and utilizing drought-resistant varieties can markedly stabilize crop output and diminish susceptibility to climate unpredictability (Beitnes *et al.,* 2024). Enhanced soil and water management strategies, including efficient irrigation and soil conservation methods, are crucial for sustaining agricultural productivity under shifting climatic circumstances. Enhancing the adaptive capabilities of farmers is also vital, requiring an increase in their access to resources, information, and institutional assistance. Social capital, encompassing networks and knowledge transfer, is essential for improving farmers' resilience and adaptive capacity (Shin, *et al.,* 2024).

CONCLUSION

The findings of this study underscore the critical relationship between modifications in agricultural land use and carrying capacity, which in turn impact on food security. Cellular Automata functions as a mechanism for anticipating changes in land utilization. This model is very effective spatially, it can be seen the location in the study area where the highest land use change in 2034 directly impacts land carrying capacity and food securityThis study indicates that the predictions are still not fully precise, owing to the assumptions that have been applied. To improve the accuracy of predictions related to land use and food security, it is essential to specify agricultural land use data, which encompasses irrigated rice fields, conventional rice fields, semi-technical rice fields, and rainfed rice fields. Then by predictions of land use with climate change forecasts will lead to more precise assessments of food security. In addition to the area of agricultural land, other factors that influence food availability in this case agricultural production are location and land management. Spatially, it can be seen that the diversity of agricultural production from 4 regencies and one city in the Special Region of Yogyakarta Province, Sleman Regency showed the highest increase in built-up land area, while in Kulonprogo Regency there was an increase in rice field area as a result of forest land conversion, so that Kulon Progo Regency could achieve surplus carrying capacity. Enhancing the agricultural land's carrying capacity is achieved by implementing a robust agricultural development strategy. The carrying capacity of agricultural land in the Special Region of Yogyakarta between 2018 and 2022 ranged from 0.0026 to 1.034. In 2018, most areas in this region had high food security. Yogyakarta City was the only city in 2018 with the lowest food security at 66.34.

In 2022, Kulon Progo Regency and Sleman Regency had a lower food security level than the previous year. Furthermore, this study underscores the vital role that maintaining and boosting agricultural land productivity plays in achieving food security. This involves optimizing land use practices and promoting sustainable agricultural methods. The potential of urban agriculture is also highlighted, especially in developing countries, as a means to increase the carrying capacity of agricultural land. In conclusion, this study delivers important findings for decision-makers, underscoring the necessity of government action in regulating agricultural land demand and anticipating its decrease. This forward-thinking method is essential for maintaining food security and promoting sustainable development in agriculture. Unexpected changes in land utilization can diminish the capacity of agricultural land and jeopardize food security. Implementation of the Regional Spatial Plan which has designated certain designated areas according to existing potential. Benefits and Penalties for Noncompliance with the Classification of sustainable agricultural areas. The findings of this study can guide future research and policy efforts to improve food security and encourage sustainable agricultural practices. In order to effectively manage land use changes and improve food security in Yogyakarta, concrete policy steps that must be implemented include 1) Prioritizing sustainable urban planning, agricultural land conservation, and technology adoption; 2) Enforce zoning laws to preserve agricultural lands and encourage the adoption of sustainable methods like agroforestry and precision agriculture; 3) Strengthen infrastructure like irrigation and storage facilities to boost productivity; 4) Invest in farmer education and support systems, including technical and financial assistance. The outlined steps can be modified for various regions by aligning policies with the specific agricultural and socioeconomic environments, which allows for adaptability while prioritizing sustainable development and food security objectives.

AUTHOR CONTRIBUTIONS

R. Harini conducted the literature review, designed the study, performed data collection, data analysis and interpretation, and prepared the article. R. Rijanta performed the literature review, analyzed and interpreted the data, especially methods. I. Sukri conducted the literature review for site selection for the study, sampling, and data collection and analyzed and interpreted the data, especially those related to location and mapping. E.H. Pangaribowo conducted the literature review for site selection for the study, sampling, and data collection and analyzed and interpreted the data, especially the food security. R.F. Putri conducted the literature review for site selection for the study, sampling, and data collection and analyzed and interpreted the data, especially the carrying capacity.

ACKNOWLEDGEMENT

The authors thank Universitas Gadjah Mada's Directorate of Research for financing this study, particularly the Academic Excellence Improvement Program Number [7725/UN1.P.II/Dit-Lit/PT.01.03/2023].

CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution, and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral concerning jurisdictional claims in published maps and

institutional afflictions.

ABBREVIATIONS

%	Percent
ANN	Artificial neural network
CA	Cellular automata
CA-ANN	Combined cellular automata and artificial neural network
CCA	Carrying capacity of agricultural
COVID-19	Coronavirus-2019
DIY	Daerah Istimewa Yogyakarata (Special Region of Yogyakarta)
eq	Equation
et al.,	Et alia (others)
etc	Et cetera (and so forth)
FIA	Food insecurity indicators
Fig.	Figure
FSI	Food security index
FSVA	Food security and vulnerability atlas
GFSI	Global Food Security Index
GHI	Global Hunger Index
ha	Hectarare
HA	harvested area
IMR	Infant mortality rate
kg	Kilogram
kg/capita/y	Kilogram per capita per year
kg/ha	kilogram per hectare
LUC	Land use change
MPN	Minimum physical needs
Po	Total population (people),
Pr	And Pr is the rice productivity
QGIS	Quantum geographic information system
RBI	Rice Bowl Index
RTRW	Rencana Tata Ruang Tata Wilayah (Spatial Planning)
SDG	Sustainable development goals
t	Time
T1	Time plus one
T2	Time plus two
Xi max	Denotes its maximum value
Xi min	Denotes its minimum value
Xij	The indicator's jth value

REFERENCES

Adebayo, H.; Oluwasegun.; Otun, W.O.; Daniel, I.S., (2019). Change detection in landuse / landcover of abeokuta metropolitan area, nigeria using multi-temporal landsat remote sensing. Indones. J. Geogr., 51(2): 217–223 (**7 pages**).

ADCIS, (2022). Analysis of food security in 2022. Agricultural data center and information system. 102 (**102 pages**).

Affoh, R.; Zheng, H.; Zhang, X.; Wang, X.; Dangui, K.; Zhang, L., (2024). Climate-Smart Agriculture as an adaptation measure to climate change in Togo: Determinants of choices and its impact on rural Households' Food Security. Agronomy. 14(7): 1-23 (**23 pages).**

Alijani, Z.; Hosseinali, F.; Biswas, A., (2020). Spatio-temporal evolution of agricultural land use change drivers: A case study from Chalous region, Iran. J. Environ. Manage., 262 (110326): 1-14 (**14 pages**).

Ashley, J.M., (2016). Food security in the developing world: Chapter Three Causes of Food Insecurity. Academic Press. 39-55 (**18 pages**).

Basir, M.S.; Chowdhury, M.; Islam, M.N.; Ashik-E-Rabbani, M., (2021). Artificial neural network model in predicting yield of mechanically transplanted rice from transplanting parameters in Bangladesh. J. Agric. Food Res., 5: 1-8 (**8 pages**).

Beitnes, S.S.; Kopainsky, B.; Potthoff, K., 2022. Climate change adaptation processes seen through a resilience lens: Norwegian farmers' handling of the dry summer of 2018. Environ. Sci. Policy. 133 (2022) 146–154 (**9 pages**).

Boutagayout, A.; Belmalha, S.; Rehali, M.; Nassiri, L.; Bouiamrine, E.H., (2023). Agroecology as agricultural practices for sustainable management in north african countries. Int. J. Plant Prod., 17(3): 389–436 (**48 pages**).

Central Bureau of Statistics, (2020). Analisis Kemiskinan Daerah Istimewa Yogyakarta. 1-5 **(5 pages).**

Costantini, D., (2015). Land-use changes and agriculture in the tropics: pesticides as an overlooked threat to wildlife. Biodivers. Conserv., 24(7): 1837–1839 (**3 pages**).

Dangulla, M.; L.A. Manaf.; Ramli, M.F., (2020). Spatio-temporal analysis of land use/land cover dynamics in Sokoto Metropolis using multi-temporal satellite data and land change modeller. Indones. J. Geogr., 52(3): 306 - 316 (**11 pages**).

Dönmez, D.; Isak, M.A.; İzgü, T.; Şimşek, Ö., (2024). Green horizons: navigating the future of agriculture through sustainable practices. Sustainability. 16(8): 1-20 (**20 pages**).

Elliot, T.; Babí Almenar, J.; Rugani, B., (2020). Modelling the relationships between urban land cover change and local climate regulation to estimate urban heat island effect. Urban For. Urban Green., 1-19 (**19 pages**).

Estacio, I.; Sianipar, C. P.; Onitsuka, K.; Basu, M.; Hoshino, S., (2023). A statistical model of land use/cover change integrating logistic and linear models: An application to agricultural abandonment. Int. J. Appl. Earth Obs. Geoinf., 120: 1-12 (**12 pages**).

Foyezur Rahman, A. N. M.; Rakib, A. A.; Akter, K. S.; Raikwar, V.; Jahir, D. M. A.; Ferdousi, J.; & Kona, M. A., (2021). Assessment

and prediction of seasonal land surface temperature change using multi-temporal Landsat images and their impacts on agricultural yields in Rajshahi, Bangladesh. Environ. Challenges. 4: 1-21 (**21 pages**).

Food Security Agency, (2020). Penyusunan dan analisis Peta Ketahanan dan Kerentanan Pangan (Peta FSVA) - 1-5 (**5 pages**).

Food Security Council, (2015). Food security and vulnerability atlas of Indonesia 2015. Dewan Ketahanan Pangan (DKP), Dewan Pertanian RI and World Food Programme (WFP), 1-70 (**70 pages**).

Fuad, A.; Mulatsih, S.; Purnamawati, H., (2019). Analysis of carrying capacity of agricultural land in supporting sustainable food self-sufficiency in Tegal Regency. IOP Conference Series: Earth Environ. Sci., 399: 1-7 (**7 pages**).

Gandharum, L.; Hartono, D.M.; Karsidi, A., (2024). Past and future land use change dynamics: assessing the impact of urban development on agricultural land in the Pantura Jabar region, Indonesia. Environ Monit Assess., 196: 645: 1-**27 (27 pages).**

Getaneh, Y.; Alemu, A.; Ganewo, Z.; Haile, A., (2022). Food security status and determinants in north-eastern rift valley of Ethiopia. J. Agric. Food Res., 8: 1-9 (**9 pages**).

Guo, Z.; Hu, Y.; Zheng, X., (2020). Evaluating the effectiveness of land use master plans in built-up land management: A case study of the Jinan Municipality, eastern China. Land Use Policy. 91: 1-20 (**20 pages**).

Iguna, S.; Sudrajat, S.; Harini, R., (2022). The profile of land carrying capacity and food security in gunungkidul regency, yogyakarta. Media Komunikasi Geografy. 23(1): 58–72 (**15 pages**).

Iqbal, S.; Ali, I., (2021). Maternal food insecurity in low-income countries: Revisiting its causes and consequences for maternal and neonatal health. J. Agric. Food Res., 3: 1-8 (**8 pages**).

Islam, K.; Rahman, F.; Jashimuddin, M., (2018). Modeling land use change using cellular automata and arti ficial neural network : the case of chunati wildlife sanctuary, bangladesh. Ecol. Indic. 88: 439–453 (**15 pages**).

Jiménez-Bedoya, A.; Fuentes-Gandara, F.; Paternina-Uribe, R.; Pinedo-Hernández, J., (2024). Perception and adaptation to climate change in vulnerable regions. Global J. Environ. Sci. Manage., 10(4): 1791-1808 (**18 pages**).

Kanianska, R., (2016). Agriculture and its impact on land-use, environment, and ecosystem services. Landscape Ecology - The influences of land use and anthropogenic impacts of landscape creation: 1–37 (**37 pages**).

Khasanah, N.N.; Gunanto, E.Y.A., (2024). Pengaruh luas panen padi, produktivitas lahan, pertumbuhan harga beras dan Jumlah Penduduk Terhadap Ketersediaan Beras Indonesia Tahun 1990 – 2022. Diponegoro J. Econ., 13(2): 67-79 (**13 pages**).

Khose, S.B.; Dhokale, K.B.; Shekhar, S., (2023). The role of precision farming in sustainable agriculture: advancements and impacts. Agric. Food E-Newsletter. 5(9): 115-119 (**6 pages**).

Kumar, L.; Chhogyel, N.; Gopalakrishnan, T.; Hasan, M. K.; Jayasinghe, S. L.; Kariyawasam, C. S.; Kogo, B. K.; Ratnayake, S., (2021). Climate change and future of agri-food production. Future Food. 49-79 (**31 pages**).

Kurowska, K.; Kryszk, H.; Marks-Bielska, R.; Mika, M.; Leń, P., (2020). Conversion of agricultural and forest land to other purposes in the context of land protection: Evidence from Polish experience. Land Use Policy. 95: 1–8 (**8 pages**).

Leroy, J. L.; Ruel, M.; Frongillo, E. A.; Harris, J.; Ballard, T.J., (2015). Measuring the food access dimension of food security. Food Nutr. Bull., 36(2): 167–195 (**29 pages**).

Liang, X.; Jin, X.; Ren, J.; Gu, Z.; Zhou, Y., (2020). A research framework of land use transition in Suzhou City coupled with land use structure and landscape multifunctionality. Sci. Total Environ., 737: 1-20 (**20 pages**).

Liu, J.; Jin, X.; Xu, W.; Gu, Z.; Yang, X.; Ren, J., (2020). A new framework of land use efficiency for the coordination among food, economy and ecology in regional development. Sci. Total Environ., 710: 1-15 (**15 pages**).

Liu, T. Y.; Su, C.W., (2021). Is transportation improving urbanization in China? Socio-Econ Plan Sci., 77: 1-10 (**10 pages**).

Liu, Y., (2018). Introduction to land use and rural sustainability in China. Land Use Policy., 74: 1–4 (**4 pages**).

Lone, S.A.; Mayer, I.A., (2019). Geo-spatial analysis of land use/ land cover change and its impact on the food security in District Anantnag of Kashmir Valley. GeoJournal. 84(3): 785–794 (**10 pages**).

Lopes, V.C.; Parente, L.L.; Baumann, L.R.F.; Miziara, F.; Ferreira, L.G., (2020). Land-use dynamics in a Brazilian agricultural frontier region. Land Use Policy. 84(3): 785–794 (**10 pages**).

McKee, A.; Beingessner, N., (2023). A literature review of the social and economic impacts of land use change. 1-36 (**36 pages**).

Meyer, M. A.; Früh-Müller, A., (2020). Patterns and drivers of recent agricultural land-use change in Southern Germany. Land Use Policy. 99: 1-11 (**11 pages**).

Mijena, G. M.; Gedebo, A.; Beshir, H. M.; Haile, A., (2022). Ensuring food security of smallholder farmers through improving productivity and nutrition of potato. J. Agric. Food Res., 10: 1 -10 (**10 pages**).

Mirzabaev, A.; Bezner Kerr, R.; Hasegawa, T.; Pradhan, P.; Wreford, A.; Cristina Tirado von der Pahlen, M.; Gurney-Smith, H., (2023). Severe climate change risks to food security and nutrition. Clim. Risk Manage., 39: 1-10 (**10 pages**).

Moreno García, R.R.; Giannetti, B.F.; Agostinho, F.; Almeida, C. M. V.B.; Sevegnani, F.; Parra Pérez, K.M.; Velásquez, L., (2021). Assessing the sustainability of rice production in Brazil and Cuba. J. Agric. Food Res., 4: 1-11 (**11 pages**).

Mota, A.A.; Lachore, S.T.; Handiso, Y.H., (2019). Assessment of food insecurity and its determinants in the rural households in Damot Gale Woreda, Wolaita zone, southern Ethiopia. Agric. Food Secur., 8(11): 1–11 (**11 pages**).

Muhammad, R.; Zhang, W.; Abbas, Z.; Guo, F.; Gwiazdzinski, L., (2022). Spatiotemporal change analysis and prediction of future land use and land cover changes using qgis molusce plugin and remote sensing big data: a case study of linyi, China. Land. 11(419): 1-24 (**24 pages**).

Muta'ali, L., (2015). Teknik analisis regional untuk perencanaan wilayah, tata ruang dan lingkungan. BPFG Universitas Gadjah Mada. 27-58 (**31 pages**).

Nasser, I. A.; Adam, E., (2024). Urbanisation in sub-saharan cities and the implications for urban agriculture: evidence-based remote sensing from niamey, niger. Urban Sci., 8(1), 5: 1-15 **(15 pages).**

Otuoze, S.H.: Hunt, D.V.: Jefferson, I., (2020). Predictive modeling of transport infrastructure space for urban growth phenomena in developing countries' cities: A case study of Kano-Nigeria. Sustainability. 13: 1–20 (**20 pages**).

Pangaribowo,: Rusdiana, (2024). Lahan pertanian di special region of yogyakarta berkurang 150 hektar setiap tahun. 1 (**1 pages**).

Parashar, A.; Mabrouki, J.; Sharma, J., (2024). AI and Smart Technologies for Smart Agriculture Environment. In: Mabrouki,

J., Azrour, M. (eds) Advanced systems for environmental monitoring, IoT and the application of artificial intelligence. Studies in Big Data. 143: 95-107 (**9 pages**).

Parven, A.; Pal, I.; Witayangkurn, A.; Pramanik, M.; Nagai, M.; Miyazaki, H.; Wuthisakkaroon, C., (2022). Impacts of disaster and land-use change on food security and adaptation: Evidence from the delta community in Bangladesh. Int. J. Disaster Risk Reduct., 78: 1-24 (**24 pages**).

Pham, T.-T.-H.; Turner, S.; Trincsi, K., (2015). Applying a systematic review to land use land cover change in northern upland vietnam: the missing case of the borderlands. Geogr. Res., 53(4): 419–435 (**17 pages**).

Pujiati, S.; Pertiwi, A.; Silfia, C.C.; Ibrahim, D.M.; Nur Hafida, S.H., (2020). Analysis of availability, affordability and utilization of food in supporting the achievement of community food security in Central Java Province. Jurnal Sosial Ekonomi Pertanian. 16(2): 123–133 (**11 pages**).

Qian, Y.; Xing, W.; Guan, X.; Yang, T.; Wu, H., (2020). Coupling cellular automata with area partitioning and spatiotemporal convolution for dynamic land use change simulation. Sci. Total Environ., 722: 1- 15 (**15 pages**).

Rahmansyah, Z.; Senjawati, N.D.; Juarini., (2020). Analisis ketahanan pangan rumah tanggamiskin berdasarkan pangsa pengeluaran pangan dan konsumsi energi di desa girirejo kecamatan imogiri kabupaten bantul. J. Dinamika Sosial Ekonomi. 21(1): 68-78 (**11 pages**).

Raza, A., Shahid, M.A., Safdar, M., Zaman, M., Sabir, R.M., Muzammal, H., Ahmed, M.M., (2024). Impact of Land Use and Land Cover Change on Agricultural Production in District Bahawalnagar, Pakistan. Environmental Sciences Proceedings. 29(1): 1-10 (**10 pages**).

Rijanta, R.; Baiquni, M.; Rachmawati, R., (2019). Patterns of livelihood changes in the displaced rural households in the vicinity of new yogyakarta international airport (NYIA). International Conference on Rural Studies in Asia (ICoRSIA): 259–263 (**5 pages**).

Rozaki, Z., (2020). Carrying capacity of agriculture sector based on commodities' production in kulonprogo regency. Adv. Eng. Res., 194: 316–319 (**4 pages**).

Saleem, A.; Anwar, S.; Nawaz, T., (2024). Securing a sustainable future: the climate change threat to agriculture, food security, and sustainable development goals. J. Umm Al-Qura Univ. Appll. Sci., 1-17 (**17 pages).**

Schneckenreither, G.; Popper, N.; Breitenecker, F., (2015). Methods for cellular automata and evolution systems in modelling and simulation., IFAC-PapersOnLine. 48(1): 141–146 (**5 pages**).

Shin, S.; Mai, I.; Sokourenko, K.; Liao, C., (2024) Everyday climate adaptation practices in agriculture contribute to food security in Sub-Saharan Africa. 29(4); 1-20 (**20 pages**).

Sfa, F.E.; Nemiche, M., (2019). A review of land use change: approaches and models. Proceedings of 2019 IEEE World Conference on Complex Systems, WCCS 2019., 4: 1–7 (**7 pages**).

Sharma, S.; Yadav, P.K.; Dahal, R.; Shrestha, S.K.; Bhandari, S.; Thapaliya, K.P., (2021). Agriculture in relation to socioeconomic status of Tharu in Chitwan of Nepal. J. Agric. Food Res., 6: 1-11 (**11 pages**).

.Singh, G.; Singh, A.; Kaur, G., (2020). Role of artificial intelligence and the internet of things in agriculture. artificial intelligence to solve pervasive internet of things issues: 317-330 (**13 pages**).

Sukri, I. ; Harini, R., ; Sudrajat, S., (2022a). Effect of transportation infrastructure on built-up area using prediction of land use/ cover change: case study of yogyakarta international airport, indonesia. Indones. J. Geogr., 55(1): 1-9 (**9 pages**).

Sukri, I. ; Harini, R., ; Sudrajat, S., (2022b). Sustainable food and agriculture strategy in kulon progo regency based on swot and spatial analysis. The 2nd International Conference on Smart and Innovative Agriculture (ICoSIA 2021): 32–39 (**8 pages**).

Sukri, I.; Harini, R.; Sudrajat, (2023). Analysis of changes in the carrying capacity of food agriculture in kulon progo regency, yogyakarta. BHUMI: J. Agraria dan Pertanahan. 8(2): 1-14 (**14 pages**).

Teklu, A.; Simane, B.; Bezabih, M., (2022). effect of climate smart agriculture innovations on climate resilience among smallholder farmers: empirical evidence from the choke mountain watershed of the blue nile highlands of ethiopia. Sustainability. 15(5): 1-26 (**26 pages**).

Tigistu, S.; Hegena, B., (2022). Determinants of food insecurity in food aid receiving communities in Ethiopia. J. Agr Food Res., 10(5): 1–28 (**28 pages**).

Tufa, D. E.; Megento, T. L., (2022). The effects of farmland conversion on livelihood assets in peri-urban areas of Addis Ababa Metropolitan city, the case of Akaki Kaliti sub-city, Central Ethiopia. Land Use Policy. 119: 1-8 (**8 pages**).

Tutunchi, H.; Ebrahimi-Mameghani, M.; Asghari-Jafarabadi, M., Farrin, N.; Tabrizi, S.; Vaghef-Mehrabany, E.; Ostadrahimi, A., (2020). Is the modified household food security survey (HFSS) questionnaire a practical tool for screening food insecurity? Evidence from northwest of Iran. BMC Public Health. 20(883): 1–11 (**11 pages**).

United Nation, (2015). The SDGS in action. What are the sustainable development goals? 1 **(1 pages).**

Vinod, C.; Hareendran, A.; Albaaji, G. F.,(2024). Precision farming for sustainability: An agricultural intelligence model. Comput. Electron. Agric., 226: 1-15 (**15 pages**).

Vogel, E.; Meyer, R., (2017). Climate change, climate extremes, and global food production—Adaptation in the agricultural sector. Resilience. 31-49 **(19 pages)**.

Wang, J.; Wei, H.; Cheng, K.; Li, G.; Ochir, A.; Bian, L.; Davaasuren, D.; Chonokhuu, S.; Nasanbat, E., (2018). Spatio-temporal pattern of land degradation along the china-mongolia railway (Mongolia). Sustainability. 11(9): 1-20 (**20 pages**).

Wang, X., (2022). Managing land carrying capacity: key to achieving sustainable production systems for food security. Land. 11(4): 1-21 (**21 pages**).

Wang, X.: Li, X., (2021). China's agricultural land use change and its underlying drivers: A literature review. J. Geogr. Sci., 31(8): 1222–1242 (**20 pages**).

Widiastuti. E.N.: Sudrajat., (2023). Pola Spasial Pemanfaatan Lahan Pertanian di Kapanewon Patuk Kabupaten Gunungkidul. Majalah Komunikasi Geografy. 25(1): 1-20 (**20 pages**).

Yikii, F.; Turyahabwe, N.; Bashaasha, B., (2017). Prevalence of household food insecurity in wetland adjacent areas of Uganda. Agric Food Security. 6(1): 1–12 (**12 pages**).

Zhang, Z.; Ghazali, S.; Miceikienė, A.; Zejak, D.; Choobchian, S.; Pietrzykowski, M.; Azadi, H., (2023). Socio-economic impacts of agricultural land conversion: A meta-analysis. Land Use Policy. 132: 1–13 (**13 pages**).

Zhang, K.; Tian, Y., (2024). Research on the spatio-temporal coupling relationship between agricultural green development efficiency and food security system in China. Heliyon. 10(11): 1-17 (**17 pages**).

AUTHOR (S) BIOSKETCHES

Harini, R., Ph.D., Associate Profesor, Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia.
▪ Email: *rikaharini@ugm.ac.id*
▪ ORCID: 0000-0002-2801-5111
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57195483722
▪ Homepage: https://acadstaff.ugm.ac.id/Rika1973

Rijanta, R., Ph.D., Profesor, Department of Development Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia.
▪ Email: *rijanta@ugm.ac.id*
▪ ORCID: 0000-0002-5374-7840
▪ Web of Science ResearcherID: AAB-5664-2021
▪ Scopus Author ID: 6503893064
▪ Homepage: https://geo.ugm.ac.id/direktoridosen/

Pangaribowo, E.H., Ph.D., Associate Profesor, Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia
▪ Email: *evitahp@ugm.ac.id*
▪ ORCID: 0000-0002-7630-6933
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 6015645
▪ Homepage: https://acadstaff.ugm.ac.id/MTk3OTA0MDAyMTIyMDAx

Putri, R.F., Ph.D., Assistant Profesor, Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia.
▪ Email: *ratihfitria.putri@ugm.ac.id*
▪ ORCID: 0000-0002-8642-4464
▪ Web of Science ResearcherID: AAB-8279-2021
▪ Scopus Author ID: 55574444300
▪ Homepage: https://acadstaff.ugm.ac.id/ratihfitria

Sukri, I., M.Sc., Assistant Profesor, Department of Geography, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Makassar, Indonesia.
▪ Email: *irwansyah.s@unm.ac.id*
▪ ORCID: 0009-0006-2988-3910
▪ Web of Science ResearcherID: LKN- 6820-2024
▪ Scopus Author ID: 58913602700
▪ Homepage: https://pend-geografi.fmipa.unm.ac.id/en/profil-dosen-2/#

HOW TO CITE THIS ARTICLE

Harini, R.; Rijanta, R.; Pangaribowo, E.H.; Putri, R.F.; Sukri, I., (2025). Modeling the effects of land use change on agricultural carrying capacity and food security. Global J. Environ. Sci. Manage., 11(2): 533-554.

DOI: 10.22034/gjesm.2025.02.10

URL: https://www.gjesm.net/article_719730.html

Global J. Environ. Sci. Manage. 11(2): 555-572, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Balancing environmental quality and economic profitability for sustainable rice-soybean cropping system

B. Phrommarat[1], N. Phrommarat[2,*]

[1] *Biology Education Program, Faculty of Education, Chiang Rai Rajabhat University, Chiang Rai, Thailand*

[2] *Mathematics Education Program, Faculty of Education, Chiang Rai Rajabhat University, Chiang Rai, Thailand*

ARTICLE INFO

Article History:
Received 20 October 2024
Revised 25 December 2024
Accepted 27 January 2025

Keywords:
Eco-optimal farming
Life Cycle Assessment (LCA)
Rice-soybean cropping system
Sustainable agriculture

ABSTRACT

BACKGROUND AND OBJECTIVES: The rice-soybean cropping system plays a significant role in the agricultural landscape of northern Thailand, providing crucial food and income sources for farmers. A major challenge persists in reconciling the economic gains provided by these systems with their environmental effects. This study analyzed the compromises between economic outcomes and environmental impacts within rice-soybean cropping systems in northern Thailand. The objective was to identify farming practices that balance profit maximization with environmental impact reduction.
METHODS: Data on the cropping system were collected from rice farmers in Chiang Rai province, located in the northernmost part of Thailand during the 2023 cropping year covering nine farms across nine different districts. The environmental impacts were quantified using life cycle assessment, while multi-objective linear programming was implemented to identify optimal agricultural practices. The analysis assessed baseline environmental performance and explored scenarios aimed at minimizing global warming potential and human toxicity potential and/or maximizing profitability.
FINDINGS: According to the baseline analysis, rice cultivation was found to have a major environmental impact, largely attributed to fertilizer usage and emissions from the fields. In contrast, soybean cultivation demonstrated a lower environmental footprint, primarily influenced by fuel consumption and herbicide application. The total impact of global warming potential and human toxicity potential in the baseline scenario were 2,855 kilogram carbon dioxide equivalent per hectare and 585 kilograms 1,4- dichlorobenzene equivalent per hectare, respectively. Profit-maximizing practices yielded the highest net profit of 1,852 United States dollars per hectare but were associated with the greatest environmental impacts. In contrast, scenarios minimizing global warming potential and human toxicity potential achieved reduced environmental harm—20 percent reduction for global warming and a 39 percent reduction for human toxicity—but at the expense of profitability. The eco-optimal farming model provided a harmonious solution, reaching close to peak profits of 1,838 United States dollars per hectare while simultaneously minimizing environmental impacts to a reasonable extent, reducing global warming to 2,459 kilograms carbon dioxide equivalent and human toxicity to 451 kilograms 1,4- dichlorobenzene equivalent per hectare).
CONCLUSION: The eco-optimal farming model highlighted the trade-offs involved in optimizing these two objectives. The profit-maximizing scenario achieved the highest net profit but led to increased environmental impacts, while scenarios focused on minimizing the environmental impacts resulted in decreased profitability. The eco-optimal farming strategy presented a harmonious balance, reaching close to peak profits while simultaneously lessening environmental impacts to a reasonable extent. These findings underscored the potential of integrating sustainable practices into the rice-soybean cropping system to enhance both economic and environmental outcomes.

DOI: 10.22034/gjesm.2025.02.11

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
49

NUMBER OF FIGURES
4

NUMBER OF TABLES
6

*Corresponding Author:
Email: *nitima.cha@crru.ac.th*
Phone: +668 9637 8879
ORCID: 0000-0001-6240-9213

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Rice is a staple crop of paramount importance, feeding more than half of the world's population and deeply influencing the culture, economy, and food security of numerous countries, particularly in Asia. As one of the foremost rice producers and exporters in the world, Thailand sees rice as a crucial component of its agricultural sector. The rice sector supports millions of Thai farmers and contributes substantially to national exports, strengthening the country's position in global food markets. Supporting 3.7 million households, rice farming is a vital source of both income and nutrition for families living in rural communities (Rakwatin *et al*., 2014). However, the sustainability of rice cultivation in Thailand faces a complex array of economic, social, and environmental challenges. Thai rice farmers have experienced various economic challenges, including volatile agricultural prices, limited access to knowledge and technology, and difficulties negotiating with middlemen (Piyaboon *et al*., 2023). Despite achieving higher yields and a reduction in poverty, Thai rice farmers are grappling with economic challenges stemming from rising production costs and falling returns (Butso and Isvilanonda, 2010). Furthermore, projections indicate that climate change will notably affect rice production in Thailand, with studies forecasting potential yield declines of 5-28 percent (%) by the mid-century century, contingent upon various regional and scenario-specific circumstances (Amnuaylojaroen *et al*., 2021; Babel *et al*., 2011). Key factors contributing to these declines include rising temperatures and shifts in precipitation patterns, which threaten to disrupt traditional growing cycles and reduce productivity (Kawasaki and Herath, 2011). Such changes could have serious economic repercussions for Thailand's rice sector, affecting both domestic food security and the country's export capacity. Rice production in Thailand faces environmental challenges due to resource-heavy practices, which involve substantial water usage, extensive pesticide application, and the release of greenhouse gases. The global warming potential of rice production ranges from 2.9 to 5.55 kilograms of carbon dioxide equivalent per kilogram (kg CO_2-eq) of rice, with rainfed systems showing lower impacts than irrigated systems (Perret *et al*., 2013). Methane emissions are a major contributor to global warming potential, with similar levels observed in northern and northeastern Thailand (Mungkung *et al*., 2020). One of the critical challenges for sustainable agriculture in Thai rice cultivation is nutrient depletion. The runoff of nitrogen and phosphorus from rice paddies poses a risk of nonpoint source pollution (Sun *et al*., 2016). Pesticide use in Thai paddy fields has increased significantly, with imports rising from 110,000 tons in 2007 to 172,000 tons in 2013 (Tawatsin *et al*., 2015). The significant utilization of these materials has caused environmental degradation, posed health threats, and contributed to pest resistance (Laohaudomchok *et al*., 2021). Studies have detected various pesticides, including organochlorines, organophosphates, and herbicides, in soil, water, and aquatic organisms (Iwai *et al*., 2007; Laohaudomchok *et al*., 2021). Human health is greatly affected, as evidenced by the annual occurrence of 49,000 to 61,000 pesticide poisoning cases, which primarily involve farmers and farm workers (Tawatsin *et al*., 2015). Pesticide contamination in paddy fields poses a significant risk to aquatic ecosystems, as rice production requires a range of pesticides to manage pests (Iwai *et al*., 2007). Recent studies have focused on sustainable methods of rice cultivation in Thailand. Mungkung *et al*. (2022) assessed sustainability using Sustainable Rice Platform indicators, finding scores ranging from 53-81% across different production systems. The study by Jaibumrung *et al*. (2023) examined ecological footprints, water scarcity footprints, and benefit-cost ratios, underscoring the significance of water management in farming activities. Chaimanuskul *et al*. (2011) developed a model for assessing sustainable agriculture, revealing regional variations in sustainability indicators. Pame *et al*. (2023) demonstrated that implementing best management practices, including laser land leveling and biofertilizers, can significantly improve economic and environmental sustainability in central Thailand. Implementing crop rotation in rice-centric farming systems has yielded positive effects on soil quality and agricultural productivity in the Southeast Asian region. In terms of ecological quality, Linh *et al*. (2017) suggested that incorporating upland crops, such as maize and mung bean, into rice rotations enhanced soil chemical properties, including increased soil organic carbon and reduced soil compaction. Furthermore, the implementation of diverse cropping systems results in prolonged and varied flowering periods, which consistently supply food for

pollinators, including bees, butterflies, and beetles. This sustains pollinator populations, critical for ecosystem health and crop productivity (Garibaldi *et al.*, 2013). Ramsden *et al*. (2017) examined how changes in farm practices affect environmental and economic outcomes in rice farming systems in Thailand using a bio-economic model combined with life cycle assessment (LCA). This study analyzed the profitability of farms and their environmental consequences across different scenarios, including the maximization of baseline profits, the minimization of greenhouse gas (GHG) emissions, and the adoption of alternative inputs. Notably, the result suggested that after GHG emissions, human toxicity showed the least improvement; this issue may require greater attention (Ramsden *et al*., 2017). In irrigated regions, it is common for farmers to plant a second crop of irrigated rice during the dry season after the rainfed rice harvest. In contrast, those outside the irrigation system often leave their fields fallow or opt for low water-demand crops such as maize, legumes, garlic, or shallots. However, growing a second crop of irrigated rice in the dry season raises sustainability concerns due to high water demand, soil degradation from intensive fertilizer use, human toxicity, and increased methane emissions (Toolkiattiwong *et al*., 2023). Conversely, leguminous crops like soybeans and mung beans present a sustainable option. They require less water, improve soil fertility through nitrogen fixation, and reduce the need for synthetic fertilizers. Additionally, legumes help break pest and disease cycles, promoting healthier and more sustainable cropping systems. In northern Thailand, soybean is commonly grown in rotation with rice, especially in regions where double-cropping is practiced. In an effort to make the most of their land and increase revenue during the dry season, farmers commonly grow soybeans after the main rice season. This practice is advantageous as the soybean growing period aligns well with the interval between rice cultivation cycles. Incorporating soybean cultivation before rice in rotation systems offers several benefits. Compared to continuous rice cultivation, it increases nitrogen availability, promotes greater diversity and activity among soil microbes, and raises the levels of extracellular enzyme activity (Carlos *et al*., 2022). By implementing this rotation, microbial diversity is significantly increased relative to ongoing upland cultivation, which in turn supports soil health and bolsters disease resistance (Hou *et al*., 2018). The organic residues from both crops provide a food source for soil fauna, such as earthworms and beneficial nematodes, which play critical roles in nutrient cycling and soil structure improvement (Brussaard *et al*., 2007). Soybean cultivation before or after rice crops in Thailand, with phosphorus fertilization, can significantly improve rice yields (Jaidee *et al*., 2013). When implementing this system, it is important to carefully evaluate other factors such as water management, soil characteristics, and prevailing market conditions. The economic returns from rice and soybean production under current cropping practices were quantified. Multi-objective linear programming (MOLP) was used to establish an eco-optimal farming (EOF) model as a decision-making tool to suggest optimized farming practices that maximize profit while minimizing environmental impacts. This study sought to analyze the trade-offs between economic and environmental performance, with the goal of identifying practices that harmonize these two aims. A life cycle assessment of rice-soybean cropping systems was conducted to measure environmental impacts associated with farming activities.This study was carried out in Chiang Rai province, Thailand in 2023.

MATERIALS AND METHODS

Study area and data acquisition for farm model

This study was conducted using data collected from rice farmers in Chiang Rai province, located in the northernmost part of Thailand (19°54’30.89”N, 99°49’57”E). The agricultural calendar in Chiang Rai is characterized by two main cropping seasons that reflect its climatic patterns: the rainy season from June to November and the dry season from December to April. Chiang Rai plays a significant role in Thailand’s agricultural sector, particularly in rice and soybean production. In the region, the practice of double-cropping, which involves the cultivation of both rice and soybean, is essential for maximizing land efficiency and securing food resources. For rice farming, data on farm inputs and outputs, production costs, yields, and selling prices were gathered by the Chiang Rai Rice Research Center, Department of Rice (CRI-RRC, 2023) during the 2023 cropping year covering nine farms across nine different districts. Lowland rice production in the northern region is typically rainfed. The onset of the cropping season

occurs during the early rainy season, usually in June or July. The duration until maturity is contingent upon the specific cultivar, as rainfed rice cultivars typically require 4 to 5 months to achieve harvest readiness. After harvesting at the end of the rainy season, farmers typically choose crops with lower water requirements, such as legumes, shallots, and leafy vegetables, which generally take around three months to reach maturity for harvest. This study focused on soybean, which is frequently chosen by farmers in the area as a rotation crop after harvesting rice. This strategy is employed to improve soil health and to create additional revenue during the dry season prior to the next agricultural cycle. Soybean production in the northern region is higher than that of other crops, accounting for over 60% of the national output (OAE, 2023). Data associated with soybean production including inputs, outputs, production costs, yield, and selling price in the 2023 cropping year was obtained from the Office of Agricultural Economics (OAE, 2023). Local market prices for fertilizers and pesticides were compiled. Table 1 provides a summary of the data sources and assumptions that were employed in the establishment of the model.

Life cycle assessment

A standard LCA framework, based on ISO14040/14044: 2006, consists of four main stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation.

Goal and scope definition

The aim of the LCA was to quantify the per-hectare (ha) environmental impacts associated with rice and soybean cultivation within the farm system. Subsequently, the results were included in the eco-optimal farming model as environmental indicators. The definition of the functional unit encompasses the cultivation of crops on an area of one hectare during a single cropping season. The system boundary was set as "cradle-to-the-farm-gate," encompassing four main processes: land preparation, sowing, crop maintenance, and harvesting, as illustrated in Fig. 1. This study intentionally omitted post-harvest activities from the system boundary to concentrate on the primary production phase, recognized as the most resource-demanding and environmentally significant stage in the rice-soybean cropping system. Data related to background systems, namely the production of farm inputs such as fertilizers, pesticides, and fuels, were obtained from the life cycle inventory (LCI) database, Ecoinvent 3.4, embedded in OpenLCA software. An evaluation of the environmental effects of the product system was performed in accordance with the CML-IA baseline. To promote clarity and ease of understanding for stakeholders, Global Warming

Table 1: Data sources and assumptions used for model establishment

+

Aspect	Details	Data source	Assumptions
Crop inputs and outputs	Data collected from nine farms in Chiang Rai during the 2023 cropping season	CRI-RRC (2023); OAE (2023)	Farms are representative of typical rice-soybean cropping systems in the region.
Direct emissions	Direct emissions to air, soil, and water from the fields	IPCC (2019); De Vries *et al.* (2023); Elhamalawy *et al.* (2024)	No significant variation in management practices across fields.
Fertilizer and pesticide use	Quantities and types of fertilizers and pesticides applied	CRI-RRC (2023); Jaipala *et al.* (2022)	Uniform fertilizer and pesticide application practices across surveyed farms.
Water use	Water requirements of crops	RID (2023)	Rainfed and irrigated areas are correctly classified and representative.
Environmental impacts	Global warming potential (GWP) and human toxicity potential (HTP)	Ecoinvent 3.4 database via OpenLCA software	Farming practices across farms are assumed to be consistent.
System boundary	Cradle-to-farm-gate (land preparation to harvest)	Study definition	Post-harvest activities are excluded.
Transportation	Movement of farm inputs (fertilizers, seeds, pesticides) to farms	Ecoinvent 3.4 database via OpenLCA software/Distance assumption based on field surveys	Average transportation distance of 5 kilometers (km), using light vehicles with consistent emission factors.

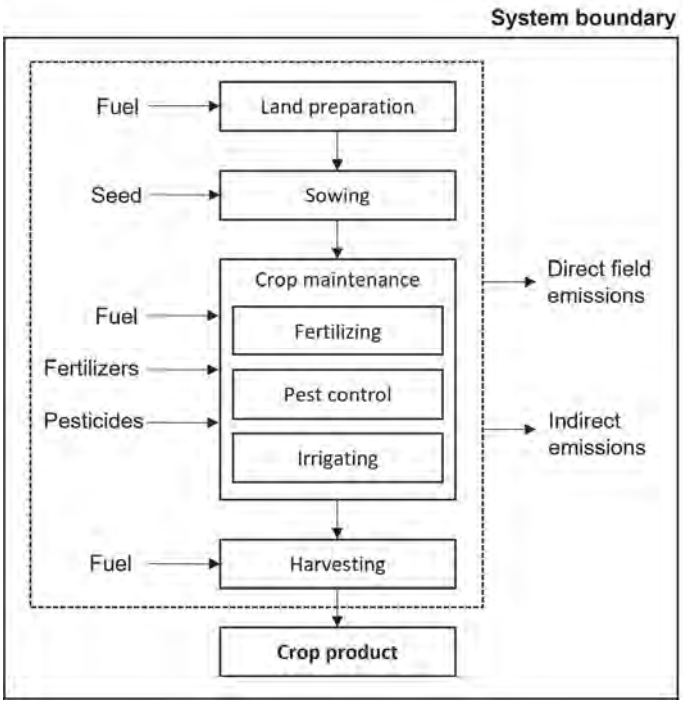


Fig. 1: The system boundary of rice and soybean cultivation LCA

Potential (GWP) and Human Toxicity Potential (HTP) were identified as the two main environmental indicators. These indicators were selected as they represent current key environmental concerns in sustainable agriculture and are directly relevant to the policy and management decisions for rice-soybean cropping systems (Ramsden *et al*., 2017; Toolkiattiwong *et al*., 2023).

Life cycle inventory

Four main stages were considered in the life cycle inventory summarized in Table 2. During land preparation, the arable land was plowed using a tractor. Rice seedlings were transplanted into the field, while soybean seeds were sown manually. During the crop maintenance phase, fertilizers were administered manually, whereas pesticides were applied using a knapsack hand pump sprayer that did not require any fuel. Data on fertilizer and pesticide usage were obtained from surveys conducted by CRI-RRC (2023) and Jaipala *et al*. (2022). It was estimated that agricultural inputs were delivered from the local retailer to the farm, covering a distance of 5 km. For rainfed rice, water was primarily obtained from rainfall. In instances of low rainfall, farmers increase their water availability by utilizing water pumps to draw additional supplies from irrigation canals. In contrast, soybean cultivation during the dry season relied heavily on irrigated water, either from adjacent canals or groundwater sources. Crop water requirements were obtained from the Royal Irrigation Department (RID, 2023). At the end of the season, rice was harvested using a combined harvester, whereas soybeans were harvested manually. The inventory of field operations, modeled using Ecoinvent agricultural processes, included resource consumption and indirect emissions associated with the production, maintenance, repair, and disposal of agricultural machinery.

Data on direct field losses and emissions were considered. Direct greenhouse gas emissions from the paddy field, including methane (CH_4) and nitrous oxide (N_2O), were calculated following the methodology of the Intergovernmental Panel on Climate Change (IPCC, 2019). Emission factors for nitrogen compounds released into water (nitrogen leaching) and air (nitrogen oxides; NO_x) from nitrogen fertilizer application were also based on

Table 2: Life cycle inventory of rice and soybean cultivation in 1 ha

	Unit	Rice	Soybean
Input parameter			
Tillage (plow)	ha	1	1
Seeds	Kilogram (kg)	62	60
Nitrogen fertilizer	kg	103.5	-
Phosphorus fertilizer	kg	41.4	-
Potassium fertilizer	kg	12.5	-
Water	Cubic meter (m^3)	5700	3290
Diesel (site-mounted mower)	l	6.25	-
Petrol (water pump)	l	2.78	28.7
Harvester	ha	1	-
Insecticide (Dinofuran)	gAI	50	-
Fungicide (Carbendazim)	gAI	125	-
Herbicide (fluazifop-p-butyl+ fomesafen)	gAI	-	400
Transport	kg*km	788	7.5
Output/direct emission			
Crop yield	kg	5623	1713
CH_4 (air)	kg	52.6	-
N_2O (air)	kg	1.58	0.608
NO_x (air)	kg	0.33	0.128
NH_3 (air)	kg	6.51	-
Nitrate leaching (water)	kg	32.2	7.35
Phosphorus leaching (water)	kg	0.27	0.25
Pesticide contamination (soil)	g	175	400

Intergovernmental Panel On Climate Change (IPCC) guidelines. Given the absence of detailed data for Thailand, estimates for ammonia (NH_3) emissions directly into the air and phosphorus losses from chemical fertilizers to groundwater and surface water were derived from the research conducted by De Vries *et al*. (2023). For pesticide emissions, it was assumed that pesticides primarily contaminated agricultural soil after application. According to the findings of Elhamalawy *et al*. (2024), only a small fraction—less than 1%—of applied pesticides interacts with the intended weeds or pests, with the majority contributing to environmental contamination. Inventory data summarized in Table 2 were used as the baseline scenario for comparison in the farm model.

The eco-optimal farming model

The EOF model employed a multi-objective linear programming approach to harmonize economic and environmental objectives in a rice-soybean cropping system. This model aims to optimize farm profitability while simultaneously decreasing environmental repercussions, with a focus on GWP and HTP. The primary model consisted of three core components: the financial net benefits of crop production, farm input and resource constraints that limit production, and the technical coefficients required per hectare for crop cultivation. The optimal solution indicated the most lucrative result possible while adhering to the specified constraints. From this maximum farm-level profit solution, the cost of shifting toward specific environmental objectives can be determined. Based on the results obtained from the LCA, coefficients reflecting the environmental impact of cropping activities were developed. Two significant impact categories were taken into account: the potential for global warming and the potential for human toxicity. Variable inputs, modeled as a linear function of crop area, allowed for the calculation of net profit per hectare for each crop. Variable costs, listed in Table 3, included expenses for land preparation, seeds, pesticides, fertilizers, and other inputs (such as labor). The EOF model effectively integrated economic and environmental analyses by utilizing a per-hectare basis, which allowed for the direct incorporation of LCA results. An initial run was conducted to establish the optimal farm plan and its associated environmental impact, serving as the baseline scenario.

The EOF model can be formulated as a Minimax MOLP problem. The decision variable x_i represents

Table 3: Average economic and physical production values of rice and soybean cultivation in the baseline scenario (in 2023 values)

Parameter	Rice	Soybean
Variable cost (USD/ha)	384±116	93±24
Yield (kg/ha)	5,623±233	1,713±102
Price (USD/kg)	0.29±0.02	0.49±0.02
Income (USD/ha)	1,630±131	839±61
Net profit (USD/ha)	1,246±175	746±66

Notes: Kilogram per hectare (kg/ha); US dollar per hectare (USD/ha); US dollar per kilogram (USD/kg)

the area (in hectares) allocated to each crop i. Acting as the minimax objective, the variable z ensures a harmonious balance between economic and environmental goals. The model aims to identify a solution that maximizes profit while reducing environmental impacts, specifically GWP and HTP, to acceptable thresholds by minimizing z, as outlined in Eq. 1 (Yang, 2000):

1) Profit maximizing constraint:

$$z \geq P^* - \sum_i P_i x_i \quad (1)$$

Where, P_i is profit per hectare for crop i, and P^* represents the maximum achievable profit.

2) Environmental impact minimization constraints, using Eq. 2 (Yang, 2000):

$$z \geq \sum_i g_i x_i - G^*, \; z \geq \sum_i h_i x_i - H^* \quad (2)$$

Where, g_i and h_i are the GWP and HTP coefficients per hectare for crop i, while G^* and H^* represent the acceptable levels for these impacts, defined based on a 10% reduction in profit, using Eq. 3 (Yang, 2000):

3) Feasibility constraints:

$$\sum_i f_i x_i \leq F_{available}, \quad x_i \geq 0 \quad (3)$$

Where, f_i is the farm input requirement (e.g., fertilizers, pesticides) per hectare for crop i, and $F_{available}$ is the total available input.

Addition criteria for alternative scenarios

Within the context of alternative inputs, the model adopted external strategies designed to mitigate the adverse environmental consequences of the agricultural system by enabling the selection of various pesticides and fertilizers. These options featured varying price and environmental metrics, which facilitated the model's ability to analyze the trade-offs between economic viability and ecological sustainability. By incorporating these options, the system gained the ability to utilize inputs with reduced GWP and HTP, even if they entail a greater expense. In the LCA baseline scenario, the two crops were assessed separately using LCA, and nutrient credits from soybean residues left in the field were not accounted for before rice cultivation, assuming no residual nutrient contributions. Conversely, the alternative scenario viewed these nutrient credits as partial replacements for chemical fertilizers, thereby decreasing dependence on synthetic inputs and emphasizing the role of enhanced resource efficiency in promoting more sustainable farming practices. According to the Department of Agriculture (DOA, 2020), soybean residues provide 12.5-37.5 kg N/ha, 0.63-3.75 kg P/ha, and 1.88-22.5 kg K/ha to the soil after plowing and burying. In the model, the median values of these ranges were used. For rice pest control, the white-backed planthopper (WBPH, *Sogatella furcifera*) was identified as a significant insect pest present in all sampled paddy fields, requiring effective management. Additionally, rice blast disease caused by *Pyricularia oryzae* was observed in several fields in the study area in 2023. The study evaluated three different insecticides for controlling WBPH and three fungicides for managing rice blast disease, all of which are readily accessible in local markets. For soybean cultivation, the primary pest issue is weed infestation. Data on herbicides for soybean weed control and their efficacy were sourced from Jaipala *et al.* (2022). The model accounts for potential yield losses that are expected in the absence of pest control. A summary of the pest control alternatives, including herbicides and their impact on yield, is provided in Table 4.

Table 4: Alternative pesticides available in the EOF model

Pest control	Pesticide name	Application rate (gAI/ha)	Cost (USD/ha)	Yield loss (%)
Rice white-backed planthopper	Dinotefuran (BL)	50	5.29	-
	Buprofezin	200	5.88	-
	Etofenprox	50	6.62	-
Rice blast disease	Carbendazim (BL)	125	1.84	-
	Isoprothiolane	104.4	4.12	-
	Kasugamycin hydrochloride hydrate	15	7.06	-
Rice no pest control			-	37.2
Soybean weed	fluazifop-p-butyl+fomesafen (BL)	400	35.90	-
	Alachlor	1500	20.74	9.8
	fenoxaprop-p-ethyl+fomesafen	325	36.58	11.7
Soybean no weed control			-	43.0

Notes: Gram of active ingredient (gAI/ha); Used in the baseline scenario (BL)

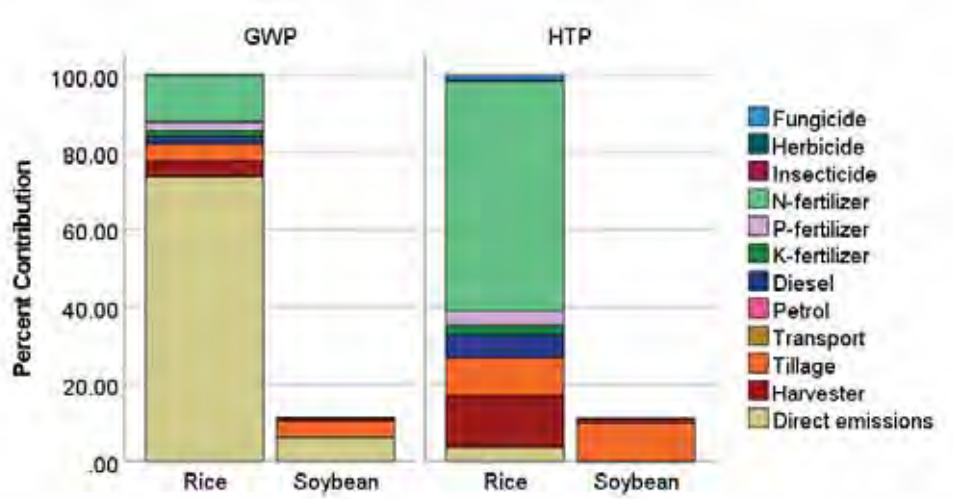


Fig. 2: Percentage contribution of farming activities of rice and soybean cultivation in the baseline scenario to GWP and HTP

RESULTS AND DISCUSSION

Life cycle impact assessment

The environmental impacts of the baseline scenario (BL) or profit-maximizing scenario for rice and soybean cultivation systems in northern Thailand were evaluated, focusing on GWP and HTP per hectare as illustrated in Fig. 2. The findings indicated clear disparities between the two crops, influenced by differences in farming methods and the application of inputs. The total impacts of GWP and HTP in the baseline scenario, where rice and soybean were evaluated separately, were 2,855 kilogram carbon dioxide equivalent per hectare (kg CO_2-eq/ha) and 585 kilograms of 1,4-dichlorobenzen equivalent per hectare (kg 1,4-DB-eq/ha), respectively. Similar results have been reported in previous studies. Yossapol (2008) assessed greenhouse gas emissions from rice cultivation in northeastern Thailand and estimated emissions at 2,908 kg CO_2-eq/ha. Correspondingly, Yodkhum *et al.* (2017) indicated that organic rice cultivation in northern Thailand generates emissions of 0.58 kg CO2-eq/kg paddy rice. This study, however, presents a reduced emission figure of 0.46 kg CO2-eq/kg paddy rice, with field emissions identified as the primary source of these emissions. Methane emissions were identified as the primary contributor to the GWP, consistent with the findings of Mungkung *et al.* (2020), who observed GHG emissions from paddy fields in northern and northeastern Thailand. Conversely, the GWP impact

Table 5: Results of the eco-optimal farming model for different objectives

Parameter	Profit maximizing		GWP minimizing		HTP minimizing		Optimal EOF	
Season	S1	S2	S1	S2	S1	S2	S1	S2
Crop	SB	RC	SB	RC	SB	RC	SB	RC
Area (ha)	1	1	1	0.8	1	0.8	1	1
SB herbicide	FL+FO	-	FL+FO	-	FE+FO	-	FL+FO	-
RC insecticide	-	DF	-	DF	-	DF	-	DF
RC fungicide	-	CZ	-	CZ	-	IP	-	KM
N-fertilizer (kg)	-	72.9	-	52.2	-	52.4	-	72.9
P-fertilizer (kg)	-	39.2	-	30.9	-	31.0	-	39.2
K-fertilizer (kg)	-	0.3	-	0.0	-	0.0	-	0.3
Yield (kg)	1,713	5,623	1,713	4,504	1,713	4,507	1,713	5,623
Net profit (USD)	1,852±106[a]		1,634±65[b]		1,634±82[b]		1,838±56[a]	
GWP (kg CO_2-eq)	2,460±123[a]		1,972±196[b]		1,976±197[b]		2,459±169[a]	
HTP (kg 1,4-DB-eq)	477±99[a]		374±41[b]		355±39[b]		451±35[a]	

Notes: SB = soybean; RC = rice; FL = fluazifop-p-butyl; FO = fomesafen; DF = dinotefuran; CZ = carbendazim; FE = fenoxaprop-p-ethyl; IP = isoprothiolane; KM = kasugamycin hydrochloride hydrate;
Different superscripted letters in each row indicate significant differences (one-way ANOVA; Tukey's test, p≤0.05)

of soybeans was notably low, with the majority of contributions coming from the use of diesel and petrol in farming machinery and emissions directly from the fields. When examining HTP, rice also dominated, with nitrogen fertilizer production being the largest contributor to toxicity. The manufacturing process of nitrogen fertilizers, notably synthetic forms such as urea and ammonium nitrate, requires significant energy and predominantly depends on fossil fuel sources. This process results in the release of pollutants, including ammonia, nitrogen oxides, and particulate matter, which are associated with respiratory issues and other adverse health effects in humans. The life cycle of nitrogen fertilizer use in grain production systems significantly contributes to fine particulate matter formation, posing substantial human health risks and leading to economic losses (Wang and Lu, 2020). Soybean's HTP impact was considerably lower, though herbicide use remained a notable contributor.

Eco-optimal farming solution

The outcomes of the eco-optimal farming model revealed considerable trade-offs between the pursuit of economic profit and the effort to minimize environmental consequences. The inputs and factors associated with these scenarios are detailed in Table 5. In the profit-maximizing scenario, the model achieved the highest net profit of 1,852 US dollar (USD)/ha, but this came at the cost of increased environmental impacts, with GWP of 2,460 kg CO_2-eq and HTP of 477 kg 1,4-DB-eq. Significantly, this situation underscored the value of using soybean residues in place of chemical fertilizers in the soil prior to rice cultivation, corroborating the conclusions drawn from previous studies (Carlos *et al.*, 2022; Jaidee *et al.*, 2013). As a result, GWP and HTP were reduced by 14% and 18%, respectively, compared to the baseline scenario.

In contrast, the GWP-minimizing scenario reduced GWP to 1,972 kg CO_2-eq, representing a 20% reduction compared to the profit-maximizing scenario. The decrease was accomplished by modifying fertilizer applications and making minor reductions to the rice cultivation area. The reduction in net profit to 1,634 USD per/ha emphasizes the conflict between achieving economic success and fulfilling environmental considerations. Similarly, the HTP-minimizing scenario achieved the lowest toxicity impact, with an HTP of 355 kg 1,4-DB-eq, by making specific adjustments to herbicide and fungicide applications. Although this approach resulted in lower efficacy and reduced soybean yield (Jaipala *et al.*, 2022), substituting fenoxaprop-p-ethyl for fluazifop-p-butyl in soybean weed control slightly decreased the human toxicity impact. Furthermore, the substitution of carbendazim with isoprothiolane for the management of rice blast disease played a significant role in achieving this reduction. Besides the adjustments made to pesticide practices, the model's suggestion to decrease the rice cultivation area played a significant role in reducing the toxicity associated with nitrogen fertilizer application. However, this scenario also led to a decreased profit of 1,634 USD/ha. The EOF optimal solution

provided a balanced solution, achieving a net profit of 1,838 USD/ha, which is only marginally lower than the profit-maximizing scenario. Simultaneously, it reduced environmental impacts to 2,459 kg CO_2-eq for GWP and 451 kg 1,4-DB-eq for HTP. Under these optimal conditions, the model advised the use of kasugamycin hydrochloride hydrate as the fungicide for rice and proposed fluazifop-p-butyl for managing weed control in soybean crops. Figs. 3 and 4 illustrate the contribution of different farm inputs to GWP and HTP across the various scenarios, respectively, based on the LCA results. This demonstrates the potential of the EOF approach to optimize trade-offs, preserving most of the economic benefits while moderately mitigating environmental impacts. Stuart *et al.* (2017) reported that adopting integrated management practices increases net farm income while reducing the use of high-impact inputs such as fertilizers, demonstrating that input use changes can yield both economic and environmental benefits. In specific regions where rice is the primary crop, the introduction of alternative crops such as shallots and mungbeans could be advantageous, depending on the soil conditions, to boost both sustainability and economic returns. Ramsden *et al*. (2017) highlighted that shallot offers high gross margins, making it an

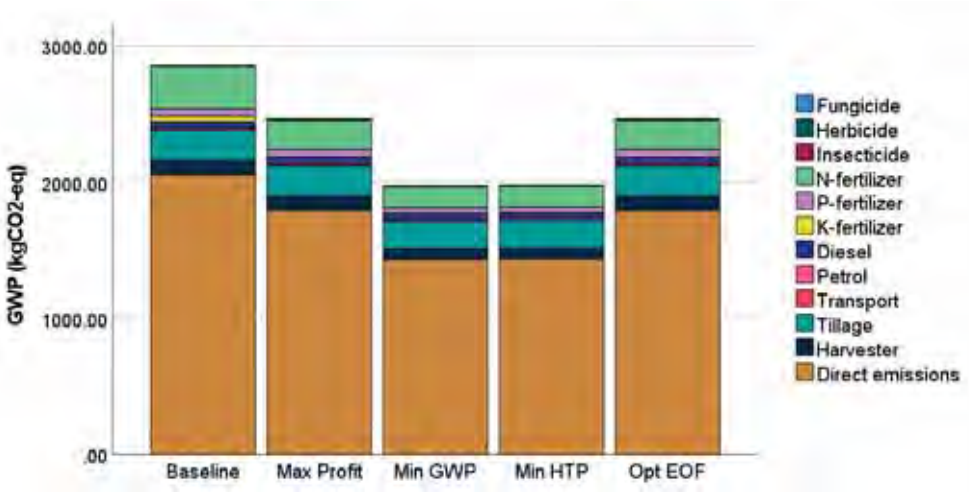


Fig. 3: The contribution of different farm inputs to GWP across the various scenarios

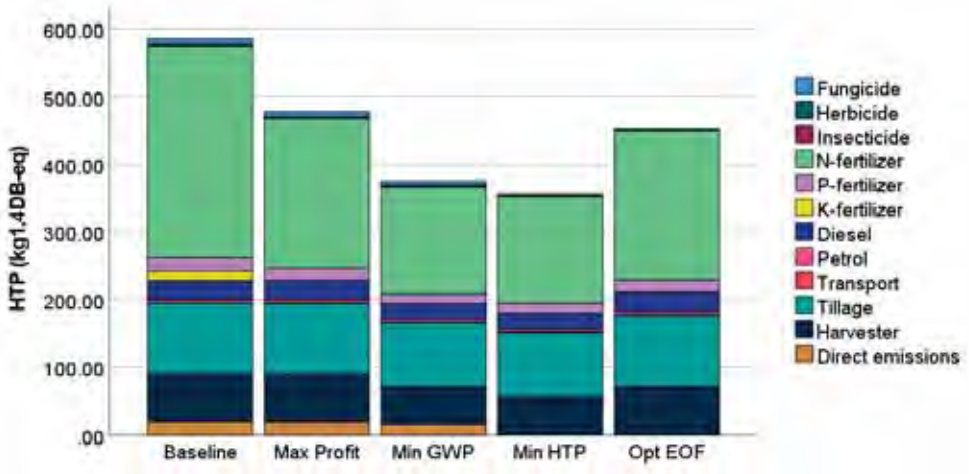


Fig. 4: The contribution of different farm inputs to HTP across the various scenarios

economically viable option for cultivation during the second and third seasons. Meanwhile, mungbean, as a leguminous crop, contributes to soil health by fixing atmospheric nitrogen and has the lowest environmental impact among the crops studied, making it a highly sustainable choice. These results emphasized the essential trade-offs involved in agricultural decision-making, revealing that the drive for higher profitability often contradicts efforts to reduce environmental consequences. The EOF approach offered a practical compromise, demonstrating its potential application in sustainable farming practices.

This study tackles important deficiencies in the existing studies regarding rice-soybean cropping systems in Southeast Asia. While previous studies have examined the sustainability of rice production in Thailand, many have focused on single-crop systems or limited environmental indicators (Mungkung *et al*., 2020; Ramsden *et al*., 2017). This study presents an innovative eco-optimal farming model that merges LCA with MOLP to assess the trade-offs between economic viability and environmental impacts within a rice-soybean rotation system. This strategy facilitates a more extensive analysis of the cropping system, considering not only the economic objectives at the farm level but also the larger environmental challenges. Key contributions include the quantification of GWP and HTP, which are critical but often overlooked environmental impact categories in the region. While previous research has emphasized methane emissions as a significant contributor to GWP in rice systems (Mungkung *et al*., 2020; Perret *et al*., 2013), this study provides a comparative analysis by including soybean cultivation, revealing its relatively lower environmental footprint but notable herbicide impacts. Furthermore, this study is one of the pioneering efforts to utilize MOLP in balancing profitability and sustainability within rice-soybean systems, successfully tackling the essential trade-offs between income maximization and environmental preservation. By exploring multiple scenarios, including profit maximization, GWP minimization, and HTP minimization, the study offers actionable insights for farmers and policymakers. However, this study was conducted with a small sample size of 9 farms across 9 districts in Chiang Rai, selected to capture diverse agro-ecological conditions and farming practices. While this sample provides valuable insights into the region's rice-soybean cropping systems, the findings may not be fully representative of all farms in northern Thailand. This constraint is due to logistical challenges and resource limitations, as comprehensive data gathering at the farm level demands considerable time and cooperation efforts. Additionally, variations in farm size and resource availability play a crucial role in determining the feasibility of adopting eco-optimal farming practices. Smaller farms with constrained resources often encounter difficulties in adopting sustainable technologies, in contrast to larger farms that usually enjoy greater adaptability in adopting these practices (Pan *et al*., 2021). These factors should be carefully considered when designing strategies for broader adoption. To mitigate potential biases, sensitivity analysis was conducted to ensure the robustness of the conclusions despite the small sample size. To strengthen the generalizability of the outcomes and to gain a wider perspective on the sustainability of the system, future studies should aim to expand the sample size

Sensitivity analysis

As volatile agricultural prices are considered a key economic challenge for local farmers (Piyaboon *et al*., 2023), the sensitivity analysis examines the impact of changes in the selling prices of rice and soybean on profitability, GWP, HTP, and the optimal farm plan. Table 6 illustrates that a 10% increase in rice selling prices results in a modest profitability enhancement of 0.5%. However, this change leads to a notable decline in GWP and HTP, which decrease by 12.1% and 13.1%, respectively. Consequently, the optimal farm plan adjusts by reducing rice cultivation to 0.84 hectares while keeping soybean cultivation steady at 1.00 ha. A 20% increase in rice selling price further amplifies these effects, with profitability rising by 0.6%, GWP decreasing by -21.8%, and HTP by -23.7%, accompanied by a further reduction in rice area to 0.75 ha. In contrast, a 10% decrease in rice selling prices results in a notable drop in profitability (-6.7%) while increasing GWP and HTP by 4.0% and 4.3%, respectively, with no changes in the farm plan. A 20% decrease exacerbates these trends, with profitability declining sharply by -15.7%, while GWP and HTP maintain similar increases (4.0% and 4.3%), and the farm plan remains unchanged.

Likewise, fluctuations in soybean market prices

Table 6: Sensitivity analysis of selling price variability on profitability, environmental impacts, and farm plan

Price variability	%change compared with BL				Farm plan (ha)
	Profit	GWP	HTP	Rice	Soybean
RC selling price +10%	0.5%	-12.1%	-13.1%	0.84	1.00
RC selling price +20%	0.6%	-21.8%	-23.7%	0.75	1.00
RC selling price -10%	-6.7%	4.0%	4.3%	1.00	1.00
RC selling price -20%	-15.7%	4.0%	4.3%	1.00	1.00
SB selling price +10%	0.3%	-7.3%	-8.0%	0.89	1.00
SB selling price +20%	0.6%	-14.6%	-15.9%	0.82	1.00
SB selling price -10%	-2.3%	4.0%	4.3%	1.00	1.00
SB selling price -20%	-6.9%	4.0%	4.3%	1.00	1.00

significantly influence both profitability and environmental consequences. A 10% increase in soybean prices raises profitability by 0.3%, while reducing GWP and HTP by -7.3% and -8.0%, respectively, as rice cultivation decreases to 0.89 ha and soybean remains at 1.00 ha. A 20% increase leads to greater benefits, with profitability increasing by 0.6%, GWP decreasing by -14.6%, and HTP by -15.9%, and rice area reduced further to 0.82 ha. Conversely, a 10% decrease in soybean prices reduces profitability by -2.3% and increases GWP and HTP by 4.0% and 4.3%, respectively, with no changes to the farm plan. A 20% decrease intensifies these losses, with profitability declining by -6.9%, while GWP and HTP exhibit the same increases of 4.0% and 4.3%, and the farm plan remains unaltered. Overall, the findings from the sensitivity analysis reveal that favorable price shifts for both crops contribute to environmental improvements by lowering rice cultivation levels, showcasing an effective land allocation approach that harmonizes profitability and sustainability. However, negative price changes significantly reduce profitability without prompting changes to the farm plan, emphasizing the vulnerability of local farmers to market volatility and the importance of price stabilization mechanisms to support sustainable agricultural practices. Approaches to reduce price volatility should encompass government subsidies, the implementation of price controls, enhancements to infrastructure, and the creation of buffer stock zones (Gaspard *et al*., 2023). Furthermore, promoting involvement in agricultural commodity exchanges and leveraging futures and options contracts can assist farmers in effectively navigating price fluctuations (Fakari *et al*., 2013). Future research could build on this by incorporating farm-level variations in parameters such as fertilizer use, water management, and other input practices. Examining these factors would provide a more comprehensive understanding of their influence on both economic and environmental outcomes, enabling more robust recommendations for sustainable agricultural practices.

Strategies for enhancing sustainability in rice-soybean cropping systems

Enhancing productivity through the management of the rice-soybean cropping system can support the adoption of sustainable practices and simultaneously mitigate environmental impacts. Efficient soil and water management are critical to sustainability. Integrated soil fertility management (ISFM) practices, such as applying organic amendments and site-specific fertilizers, improve soil health while reducing reliance on synthetic inputs (Vanlauwe *et al*., 2010). Water-saving techniques, such as Alternate Wetting and Drying (AWD) for rice and efficient irrigation systems for soybean, conserve water resources, reduce methane emissions from paddy fields, and enhance resilience to climate variability. A study carried out in Thailand revealed that the implementation of AWD not only decreases methane emissions but also preserves rice yields and enhances water conservation efforts (Chidthaisong *et al*., 2018). However, relying heavily on specific fungicides or herbicides poses significant risks, particularly the development of pest and pathogen resistance. Prolonged use of a single chemical or chemical group enables pests and pathogens to adapt, rendering these treatments less effective. Herbicide resistance in weeds, exemplified by glyphosate-resistant Amaranthus species, has emerged as a worldwide challenge, contributing to greater weed populations and elevated production expenses (Heap, 2014). Integrated Pest Management (IPM) is recommended as a sustainable approach to mitigate these challenges. IPM combines strategies, including biological control, to reduce crop yield

losses while minimizing environmental impacts (Baker *et al*., 2020). By employing precision pesticide application techniques, informed by monitoring tools, the application of chemicals is limited to essential instances, which helps to lower the risks of toxicity to humans and the environment. Furthermore, implementing crop rotation and intercropping is crucial for promoting soil health and effective pest control. Rotating field crops with legumes, such as mung bean, soybean, and peanut, enhances nitrogen fixation, reducing the need for synthetic fertilizers (Linh *et al*., 2017). Intercropping increases biodiversity, promotes pest resilience, and supports overall ecosystem health. Additionally, climate-resilient practices, including drought- and flood-tolerant crop varieties and agroforestry systems, help crops withstand environmental stresses. These methods aid in carbon sequestration by incorporating diverse crop residues into the soil, thereby promoting the development of organic matter (Kaur *et al*., 2020; Toensmeier, 2024). Transitioning to organic or semi-organic practices is a promising strategy that offers both profitability and environmental benefits by providing premium prices for products and reducing long-term input costs, despite potentially lower yields in some cases. However, challenges during the transition period, such as reduced yields and higher labor demands, can temporarily affect profitability. In order to enable this transition, stakeholders should focus on developing capacity-building programs, offering financial incentives, and establishing market connections to aid farmers in overcoming initial challenges and securing sustainable, long-term advantages (Pathania *et al*., 2024). In terms of socio-economic aspects, farmers' adoption of sustainable practices is often hindered by socio-cultural barriers, including traditional farming habits, financial constraints, and a lack of awareness about long-term benefits. Addressing these challenges requires capacity-building programs, financial incentives, and farmer-to-farmer knowledge exchange to build trust and motivation. The positive outcomes of adopting sustainable practices—such as greater profitability, enhanced soil health, improved yields, and lower environmental impacts—provide significant motivation for their implementation (Buck and Palumbo-Compton, 2022). These tangible and immediate benefits align closely with farmers' priorities, making them effective drivers of change. Carbon pricing mechanisms further incentivize sustainable practices by imposing a cost on carbon pollution and enabling farmers to earn revenue through carbon credits generated by sustainable practices (Adhisankaran *et al*., 2024). The adoption of sustainable cropping systems, such as rice-soybean rotations, strengthens local economies by creating opportunities for income diversification and reducing input costs through practices like nitrogen fixation. These strategies enhance the ability of farmers to withstand market fluctuations and contribute to the economic stability of agricultural communities. In terms of food security, integrating sustainable practices enhances agricultural productivity and reduces risks from crop failures caused by extreme weather or pest outbreaks. Diversifying crops contributes to a reliable food supply and enhances the nutritional variety available to local communities. Moreover, the cultural preferences and dietary habits of the local population influence the demand for rice and soybeans, which directly impacts sustainability planning. Understanding these preferences helps align cropping systems with market demands, ensuring both economic viability and relevance to community needs. Furthermore, the findings contribute to regional policy development by identifying strategies to optimize land allocation and input use. An illustration of this is the transition from rice farming to soybean cultivation, which can lead to greater profitability in particular market conditions and lessen environmental repercussions, facilitating the adoption of more sustainable agricultural practices. This aligns with recent calls to integrate leguminous crops into rice rotations to improve soil health and reduce dependence on chemical fertilizers (Carlos *et al*., 2022; Linh *et al*., 2017). While this study focuses on GWP and HTP due to their relevance to current policy discussions, future research should expand to include additional environmental indicators, such as water footprint, biodiversity impacts, and soil degradation. By not considering labor dynamics as a constraint or social indicator in this study, the inclusion of labor analysis could significantly enrich the understanding of both the feasibility and equity associated with the adoption of eco-optimal practices. Life cycle costs of inputs, such as fertilizers, pesticides, and water use, also have significant implications for long-term sustainability. For example, fertilizers and pesticides contribute to environmental degradation

through production emissions, runoff, and residue accumulation, while excessive water use strains local resources in areas with limited availability. The inclusion of life cycle cost analysis in future research efforts would assist in quantifying these externalities, thereby enhancing the understanding of trade-offs and promoting more sustainable decision-making. Furthermore, it is crucial to address price volatility, which poses a major economic challenge for farmers (Piyaboon *et al*., 2023) underscores the importance of price stabilization mechanisms and alternative income sources to enhance farmers' resilience and support sustainable agricultural transitions.

CONCLUSION

This study conducted a detailed assessment of the economic and environmental performance of the rice-soybean cropping system in northern Thailand using life cycle assessment and multi-objective linear programming. By focusing on the Chiang Rai province, the study addresses a critical research gap in Southeast Asia where rice-soybean rotations are common, but comprehensive sustainability assessments are lacking. The conclusions drawn from the study yield insights that is directly applicable to regional agricultural policy, including guidance on subsidies, co-benefits, and sustainable cropping practices that are customized to local circumstances. The findings emphasize the complex trade-offs inherent in agricultural systems between maximizing profitability and minimizing environmental impacts, particularly global warming and human toxicity. The baseline analysis revealed that rice cultivation is a significant contributor to environmental impacts, with GWP reaching 2,855 kg CO_2-eq/ha and HTP at 585 kg 1,4-DB-eq/ha. These significant impacts are largely attributed to methane emissions from rice cultivation and the rigorous application of nitrogen fertilizers, resulting in both direct emissions from agricultural practices and indirect emissions from the fertilizer production process. In contrast, soybean cultivation exhibited a lower overall environmental footprint, although herbicide use and fuel consumption for irrigation contributed to its impacts. The eco-optimal farming model illustrated a practical method for achieving a balance among these trade-offs effectively. The profit-maximizing scenario achieved the highest net profit of 1,852 USD/ha but led to elevated environmental impacts, with GWP and HTP reductions of only 14% and 18%, respectively, compared to the baseline. Conversely, the GWP-minimizing and HTP-minimizing scenarios achieved significant reductions in environmental impacts but at the expense of profitability, leading to net profits dropping to 1,634 USD/ha. The eco-optimal solution provided a balanced outcome, yielding a near-maximal profit of 1,838 USD/ha while reducing GWP to 2,459 kg CO_2-eq and HTP to 451 kg 1,4-DB-eq. This scenario was founded on improved practices, incorporating kasugamycin hydrochloride hydrate as a fungicide for rice, fluazifop-p-butyl for controlling weeds in soybeans, and making tactical changes to fertilizer application strategies. The broader implications of this study extend beyond the regional context. The methodology and findings provide actionable insights for policymakers and stakeholders aiming to implement sustainable agricultural practices in other regions with similar cropping systems. By emphasizing the role of sustainable practices such as Alternate Wetting and Drying (AWD), Integrated Soil Fertility Management (ISFM), and Integrated Pest Management (IPM), this study contributes to the global discourse on climate-resilient agriculture. Moreover, it underscores the necessity for supportive policies, such as mechanisms for carbon pricing, financial assistance for sustainable inputs, and incentives aimed at crop diversification, to facilitate the broad implementation of sustainable practices. Future research should address additional environmental indicators, such as water footprint, biodiversity impacts, and soil degradation, for a more holistic understanding of the sustainability of rice-soybean systems. Broadening the data collection efforts to encompass larger and more varied sample sizes will improve the generalizability of the results and offer a more robust foundation for formulating recommendations tailored to specific regions. By integrating these aspects, future studies can further advance sustainable agricultural practices and contribute to global efforts to mitigate climate change while ensuring food security.

AUTHOR CONTRIBUTIONS

B. Phrommarat, as the first author, was responsible for conceptualization, data compilation, life cycle assessment analysis, result interpretation, and manuscript preparation. N. Phrommarat, as the corresponding author, contributed to the

mathematical formulation and calculations for the multi-objective linear programming, conducted the literature review, and was involved in manuscript preparation, review, and editing.

ACKNOWLEDGEMENT

This study was kindly supported by Chiang Rai Rajabhat University. The authors would like to express their gratitude to the Chiang Rai Rice Research Center, Department of Rice, for providing essential data that contributed to this research.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
1,4-DB-eq	1,4-dichlorobenzene equivalent
AWD	Alternate wetting and drying
BL	Baseline scenario
CH_4	Methane
CO_2-eq	Carbon dioxide equivalent
CRI-RRC	Chiang rai rice research center
CZ	Carbendazim
DB-eq/ha	Dichlorobenzene equivalent per hectare
DF	Dinotefuran
DOA	Department of agriculture (of Thailand)
e.g.	(exempli gratia) For example
EOF	Eco-optimal farming
FE	Fenoxaprop-p-ethyl
$F_{available}$	Total available input
f_i	Farm input requirement per hectare for crop *i*
FL	Fluazifop-p-butyl
FO	Fomesafen
g	Gram
g_i	Global warming potential coefficient per ha for crop *i*
gAI	Gram of active ingredient
GHG	Greenhouse gas
GWP	Global warming potential
ha	Hectare
h_i	Human toxicity potential coefficient per ha for crop *i*
HTP	Human toxicity potential
IP	Isoprothiolane
i	type of crop
IPCC	Intergovernmental Panel On Climate Change
IPM	Integrated pest management
ISFM	Integrated soil fertility management
ISO	International organization for standardization
K	Potassium
kg	Kilogram
kg CO_2-eq/ha	Kilogram carbon dioxide equivalent per hectare

km	Kilometer
KM	Kasugamycin hydrochloride hydrate
L	Litre
LCA	Life cycle assessment
LCI	Life cycle inventory
m^3	Cubic meter
Max	Maximizing
Min	Minimizing
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO_x	Nitrogen oxides
OAE	Office of agricultural economics (of Thailand)
Opt	Optimal
*P**	Maximum achievable profit
P_i	Profit per hectare of crop *i*
RC	Rice
SB	Soybean
USD	US dollar
WBPH	White-backed planthopper
x_i	Area (hectare) allocated to crop *i*
z	Minimax objective

REFERENCES

Adhisankaran, K.; Manivannan, V.; Sakthivel, N.; Balachandar, D.; Ragunath, K.; Vasumathi, V., (2024). Agricultural carbon credits: A pathway to environmental sustainability. Plant Sci. Today. 11(4): 1200-1211 **(12 pages)**.

Amnuaylojaroen, T.; Chanvichit, P.; Janta, R.; Surapipith, V., (2021). Projection of rice and maize productions in northern Thailand under climate change scenario RCP8.5. Agriculture. 11(1): 23 **(15 pages)**.

Babel, M.S.; Agarwal, A.; Swain, D.K.; Herath, S., (2011). Evaluation of climate change impacts and adaptation measures for rice cultivation in Northeast Thailand. Clim. Res., 46: 137-146 **(10 pages)**.

Baker, B.P.; Green, T.A.; Loker, A., (2020). Biological control and integrated pest management in organic and conventional systems. Biol. Control., 140: 104095 **(9 pages)**.

Brussaard, L.; De Ruiter, P.C.; Brown, G.G., (2007). Soil biodiversity for agricultural sustainability. Agric. Ecosyst. Environ., 121(3): 233-244 **(12 pages)**.

Buck, H.J.; Palumbo-Compton, A., (2022). Soil carbon sequestration as a climate strategy: what do farmers think?. Biogeochemistry. 161: 59-70. **(12 pages)**.

Butso, O.; Isvilanonda, S., (2010). Two Decades of the Rice Economy of Thailand. Appl. Econ., 17(1): 70-92 **(23 pages)**.

Carlos, F.S.; Schaffer, N.; Mariot, R.F.; Fernandes, R.; Boechat, C.L.; Roesch, L.F.; Camargo, F.A., (2022). Soybean crop incorporation in irrigated rice cultivation improves nitrogen availability, soil microbial diversity and activity, and growth of ryegrass. Appl. Soil Ecol., 170: 104313 **(11 pages)**.

Chaimanuskul, K.; Punnakanta, L.; Sonchaem, W.; Sukreeyapongse, P.; Hutacharoen, R., (2011). A practice model for sustainable agriculture assessment: a case study of the sustainable cultivation of Thai Hom Mali (Jasmine) rice in Thailand. Environ. Nat. Resour. J., 9(3): 12-28 **(17 pages)**.

CRI-RRC, (2023). Summary of activities for rice pest outbreak warnings under the large-scale agriculture promotion system project for the 2023 rice growing season. Chiang Rai Rice Research Center. Department of Rice, Chiang Rai.

Chidthaisong, A.; Cha-un, N.; Rossopa, B.; Buddaboon, C.; Kunuthai, C.; Sriphirom, P.; Towprayoon, S.; Tokida, T.; Padre, A.T.; Minamikawa, K., (2018). Evaluating the effects of alternate wetting and drying (AWD) on methane and nitrous oxide emissions from a paddy field in Thailand. Soil Sci. Plant Nutr., 64(1): 31-38 **(8 pages)**.

De Vries, W.; Kros, J.; Cees Voodg, J.; Ros, G.H., (2023). Integrated assessment of agricultural practices on large scale losses of ammonia, greenhouse gases, nutrients and heavy metals to air and water. Sci. Total Environ., 857: 159220 **(23 pages)**.

DOA, (2020). Soil, fertilizer, and residue management to reduce cost and increase the yield of leguminous crops. Department of Agriculture, Bangkok.

Elhamalawy, O.; Bakr, A.; Eissa, F., (2024). Impact of pesticides on non-target invertebrates in agricultural ecosystems. Pestic. Biochem. Physiol., 202: 105974 **(15 pages)**.

Fakari, B.; Farsi, M.M.; Kojouri, M., (2013). Determining fluctuations and cycles of corn price in Iran. Agric. Econ., 59(8): 373-380 **(8 pages)**.

Garibaldi, L.A.; Steffan-Dewenter, N.; Winfree, R.; Aizen, M.A.; Bommarco, R.; *et al*., (2013). Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science. 339(6727): 1608-1611 **(4 pages)**.

Gaspard, N.; Charles, K.; Muraya, A.M.; Alice, U.; Fidele, H; Mbabazize, M., (2023). Effect of agricultural products price fluctuations on smallholder farmer's welfare in Rwanda. A case study of Gicumbi, Nyagatare, Nyaruguru, Rubavu Districts. Int. J. Agric. Appl. Sci., 4(1): 43-49 **(7 pages)**.

Heap, I., (2014). Global perspective of herbicide-resistant weeds. Pest. Manage. Sci., 70(9): 1306-1315 **(10 pages)**.

Hou, P.F.; Chien, C.H.; Chiang-Hsieh, Y.F.; Tseng, K.C.; Chow, C.N.; Huang, H.J.; Chang, W.C., (2018). Paddy-upland rotation for sustainable agriculture with regards to diverse soil microbial community. Sci. Rep., 8: 7966 **(9 pages)**.

IPCC, (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E.; Tanabe, K.; Kranjc, A.; Baasansuren, J.; Fukuda, M.; Ngarize S.; Osako, A.; Pyrozhenko, Y.; Shermanau, P.; Federici, S., (eds). IPCC, Switzerland.

Iwai, C.B.; Sujira, H.; Somparn, A.; Komarova, T.; Mueller, J.M.; Noller, B.N., (2007). Monitoring Pesticides in the Paddy Field Ecosystem of North-Eastern Thailand for Environmental and Health Risks. In: Kennedy, I.R.; Solomon, K.R.; Gee, S.J.; Crossan, A.N.; Wang, S.; Sanchez-Bayo, F., (eds.). Rational Environmental Management of Agrochemicals: Risk Assessment, Monitoring,

and Remedial Action. Oxford University Press, USA.
Jaibumrung, K.; Nilsalab, P.; Gheewala, S.H.; Musikavong, C., (2023). Ecological footprint, water scarcity footprint, and benefit to cost ratio analysis towards sustainable rice production in Thailand. Sustainable Prod. Consumption. 39: 79-92 **(14 pages)**.
Jaidee, R.; Polthanee, A.; Saenjan, P.; Kirkham, M.B.; Promkhambut, A., (2013). Pre- or post- rice soybean production with phosphorus fertilization under rainfed conditions. Aust. J. Crop Sci., 7(1): 22-31 **(10 pages)**.
Jaipala, S.; Phunchaisri, J.; Pavadee, P., (2022). Use of herbicides to control weeds for increasing soybean yield after rice cultivation. Thai Agric. Res. J., 40(1): 98-108 **(11 pages)**.
Kawasaki, J.; Herath, S., (2011). Impact assessment of climate change on rice production in Khon Kaen province, Thailand. J. Int. Soc. Southeast Asian Agric. Sci., 17(2): 14-28 **(15 pages)**.
Kaur, G.; Singh, G.; Motavalli, P.P.; Nelson, K.A.; Orlowski, J.M.; Golden, B.R., (2020). Impacts and management strategies for crop production in waterlogged or flooded soils: A review. Agron. J., 112(3): 1475-1501 **(27 pages)**.
Laohaudomchok, W.; Nankongnab, N.; Siriruttanapruk, S.; Klaimala, P.; Lianchamroon, W.; Ousap, P.; Jatiket, M.; Kajitvichyanukul, P.; Kitana, N.; Siriwong, W.; Hemachudhah, T.; Satayavivad, J.; Robson, M.; Jaacks, L.; Barr, D.B.; Kongtip, P.; Woskie, S., (2021). Pesticide use in Thailand: Current situation, health risks, and gaps in research and policy. Hum. Ecol. Risk. Assess., 27(5): 1147–1169 **(23 pages)**.
Linh, T.B.; Guong, V.T.; Tran, V.T.; Khoa, L.V.; Olk, D.C.; Cornelis, W., (2017). Effects of crop rotation on properties of a Vietnam clay soil under rice-based cropping systems in small-scale farmers' fields. Soil Res., 55(2): 162-171 **(10 pages)**.
Mungkung, R.; Sitthikitpanya, S.; Dangsiri, S.; Gheewala, S.H., (2020). Life cycle assessment of Thai Hom Mali rice to support the policy decision on organic farming area expansion. Sustainability. 12(15): 6003 **(14 pages)**.
Mungkung, R.; Sitthikitpanya, S.; Chaichana, R.; Bamrungwong, K.; Santitaweeroek, Y.; Jakrawatana, N.; Silalertruksa, T.; Gheewala, S.H., (2022). Measuring sustainability performance of rice cultivation in Thailand using Sustainable Rice Platform indicators. Int. J. Agric. Sustainability. 20(7): 1278 – 1293 **(16 pages)**.
OAE, (2023). Agricultural statistics of Thailand 2023. Office of Agricultural Economics, Bangkok.
Pame, A.R.; Vithoonjit, D.; Meesang, N.; Balingbing, C.; Gummert, M.; Van Hung, N.; Singleton, G.R.; Stuart, A.M., (2023). Improving the sustainability of rice cultivation in central Thailand with biofertilizers and laser land leveling. Agronomy. 13(2): 587 **(18 pages)**.
Perret, S.R.; Thanawong, K.; Basset-Mens, C.; Mungkung, R., (2013). The environmental impacts of lowland paddy rice: a case study comparison between rainfed and irrigated rice in Thailand. Cahiers Agricultures. 22(5): 369-377 **(9 pages)**.
Pan, D.; Tang, J.; Zhang, L.; He, M.; Kung, C., (2021). The impact of farm scale and technology characteristics on the adoption of sustainable manure management technologies: Evidence from hog production in China. J. Clean. Prod., 280: 124340 **(14 pages)**.
Pathania, S.; Kumar, A.; Dhiman, S.R.; Bhardwaj, G.; Kumar, S.; Ghosh, S., (2024). The Transition from Conventional Farming to Regenerative Agriculture: Problem, Global Reality, and Future Perspectives. In: Kumar, S., Meena, R.S., Sheoran, P., Jhariya, M.K. (eds) Regenerative Agriculture for Sustainable Food Systems. Springer, Singapore.
Piyaboon, C.; Namwong, K.; Tangprecharpanich, P.; Charoenwongmit, W., (2023). The challenges of agricultural management of farmers in Suphanburi province. The EUrASEANs: J. Global Soc. Econ. Dyn., 5(42): 58-70 **(13 pages)**.
Rakwatin, P.; Prakobya, A.; Sritarapipat, T.; Khobkhun, B.; Pannangpetch, K.; Sobue; Oyoshi, K.; Okumura, T.; Tomiyama, N., (2014). Rice crop monitoring in Thailand using field server and satellite remote sensing. FAO.
Ramsden, S.J.; Wilson, P.; Phrommarat, B., (2017). Integrating economic and environmental impact analysis: the case of rice-based farming in northern Thailand. Agric. Syst., 157: 1-10 **(11 pages)**.
RID, (2023). Crop water requirements CWRdata. Royal Irrigation Department, Bangkok.
Stuart, A.M.; Pame, A.R.; Vithoonjit, D.; Viriyangkura, L.; Pithuncharurnlap, J.; Meesang, N.; Suksiri, P.; Singleton, G.R.; Lampayan, R.M., (2017). The application of best management practices increases the profitability and sustainability of rice farming in the central plains of Thailand. Field Crops Res., 220: 78-87 **(10 pages)**.
Sun, X.; Liang, X.; Zhang, F.; Fu, C., (2016). A GIS-based upscaling estimation of nutrient runoff losses from rice paddy fields to a regional level. J. Environ. Qual., 45(6): 1865-1873 **(9 pages)**.
Tawatsin, A.; Thavara, U.; Siriyasatien, P., (2015). Pesticides used in Thailand and toxic effects to human health. Med. Res. Arch., 3: 1-10 **(11 pages)**.
Toensmeier, E., (2024). Perennial staple crops and agroforestry for climate change mitigation. In: Montagnini, F. (ed.). Integrating landscapes: agroforestry for biodiversity conservation and food sovereignty. Springer, Cham: 349-452 **(104 pages)**.
Toolkiattiwong, P.; Arunrat, N.; Sereenonchai, S., (2023). Environmental, Human and Ecotoxicological Impacts of Different Rice Cultivation Systems in Northern Thailand. Int. J. Environ. Res. Public Health. 20(3): 2738 **(18 pages)**.
Vanlauwe, B.; Bationo, A.; Chianu, J.N.; Giller, K.E.; Merckx, R.; Mokwunye, U.; Ohiokpehai, O.; Pypers, P.; Tabo, R.; Shepherd, K.D.; Smaling, E.M.; Woomer, P.L.; Sanginga, N., (2010). Integrated Soil Fertility Management. Outlook Agric., 39(1): 17 – 24 **(8 pages)**.
Wang, Y.; Lu, Y., (2020). Evaluating the potential health and economic effects of nitrogen fertilizer application in grain production systems of China. J. Clean. Prod., 264: 121635 **(11 pages)**.
Yang, J.B., (2000) Minimax reference point approach and its application for mutiobjective optimization. Eur. J. Oper. Res., 126: 541-556 **(16 pages)**.
Yodkhum, S.; Gheewala, S.H.; Sampattagul, S., (2017). Life cycle GHG evaluation of organic rice production in northern Thailand. J. Environ. Manage., 196: 217-223 **(7 pages)**.
Yossapol, C., (2008). Life cycle assessment of rice production in Thailand. In: Abstract, 6th International Conference on LCA in the Agi-Food Sector. Zurich: Agroscope Reckenholz-Tänikon Research Station ART: 77-78 **(2 pages)**.

AUTHOR (S) BIOSKETCHES

Phrommarat, B., Ph.D., Assistant Professor, Biology Education Program, Faculty of Education, Chiang Rai Rajabhat University, Bandu, Chiang Rai, Thailand.
- Email: *bhanupong.phr@crru.ac.th*
- ORCID: 0000-0002-4757-9406
- Web of Science ResearcherID: AAC-6519-2021
- Scopus Author ID: 57194601998
- Homepage: https://edu.crru.ac.th/edu2022/home/vichakarn#!

Phrommarat, N., Ph.D., Assistant Professor, Mathematics Education Program, Faculty of Education, Chiang Rai Rajabhat University, Bandu, Chiang Rai, Thailand.
- Email: *nitima.cha@crru.ac.th*
- ORCID: 0000-0001-6240-9213
- Web of Science ResearcherID: NA
- Scopus Author ID: 57221133565
- Homepage: https://edu.crru.ac.th/edu2022/home/vichakarn#!

HOW TO CITE THIS ARTICLE

Phrommarat, B.; Phrommarat, N., (2025). Balancing environmental quality and economic profitability for sustainable rice-soybean cropping system. Global J. Environ. Sci. Manage., 11(2): 555-572.

DOI: 10.22034/gjesm.2025.02.11

URL: https://www.gjesm.net/article_720267.html

Global J. Environ. Sci. Manage. 11(2): 573-592, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

The impacts of land use and cover change on water quality of watershed basin

D.P. Marisi[1], S. Suprihatin[2,*], S. Hariyadi[3], R.L. Kaswanto[4]

[1] *Natural Resources and Environmental Management Sciences, Graduate Study Program, IPB University, Bogor,16680, Indonesia*

[2] *Department of Agroindustrial Technology, Faculty of Agricultural Engineering and Technology, IPB University, Bogor, 16680, Indonesia*

[3] *Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Bogor, 16680, Indonesia*

[4] *Department of Landscape Architecture, Faculty of Agriculture, IPB University, Bogor, 16680, Indonesia*

ARTICLE INFO

Article History:
Received 02 September 2024
Revised 06 December 2024
Accepted 10 January 2025

Keywords:
Cileungsi River
Land use land cover (LULC)
Pearson correlation
Spatio-temporal analysis
Water quality assessment

ABSTRACT

BACKGROUND AND OBJECTIVES: Land use and cover change are the leading causes of water quality decline in a body of water. However, understanding spatial and temporal variability in land use and land cover change and its relationship with water quality parameters in the eucledian distance area is still limited. In order to address these constraints, the study explored the relationship between changes in land use and land cover and their effects on water quality parameters, including chemical, physical, and biological aspects, within the Upper Bekasi Watershed, West Java, Indonesia. This study aims to explore the connection between different types of land cover and the water quality of rivers within the designated.
METHODS: Water quality data of Upper Bekasi Watershed comes from six monitoring stations. The river water quality monitoring data period is 4 years, 2018-2022, excluding 2020. The monitoring process includes 15 parameters related to water quality, addressing chemical, physical, and biological charactristics. The water sub-catchment area employs a Euclidean distance-based approach, and land use and land cover classes are obtained based on Landsat image data processed using Geographic Information System. Measurement of Pearson correlation is carried out to determine whether there is a linear relationship between the and use and land cover change variable, considered an independent variable, and the water quality variable as a dependent variable. The primary purpose of principal component analysis is to ascertain the significant water parameters influencing the variability in the dataset. The calculation of the Pearson correlation coefficient and Principal component analysis use statistical package for the social sciences.
FINDINGS: The land use and land cover change class in the Upper Bekasi Watershed obtained five classes: built-up areas, agriculture and forests occupying more than 90 percent of the Upper Bekasi Watershed area. From 2018 to 2022, there was a 10.38 percent rise in the built-up area, in contrast to an 11.57 percent reduction in agricultural land. The concentration of nitrate, nitrite, phosphate, copper and fecal coliform experienced an increasing trend at all monitoring stations every year. Conversely, the river water quality standards were only satisfied by the total dissolved solids and nitrate parameters. A significant relationship exists between forest cover and levels of dissolved oxygen and phosphate, as well as between agricultural areas and nitrite and chemical oxygen demand. Additionally, built-up regions show a strong association with fecal coliform levels. The number of key component obtained three components: the first varifactors had a strong relationship with the total suspended solids, biochemical oxygen demand, and chemical oxygen demand, the second varifactor had a relationship with the total dissolved solids, and the third varifactor had a relationship with the potential of hydrogen and fecal coliform.
CONCLUSION: The correlation between land use and land cover changes and water quality in the Upper Bekasi watershed was quantified using the Pearson correlation coefficient and principal component analysis. The analysis revealed that changes in land use and land cover had a notable influence on the water quality within the Upper Bekasi watershed. The results of this study can be used as a basis for water quality management in the Upper Bekasi watershed to help stakeholders select intervention methods to control wastewater pollution.

DOI: 10.22034/gjesm.2025.02.12

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
55

NUMBER OF FIGURES
6

NUMBER OF TABLES
6

*Corresponding Author:
Email: *suprihatin@apps.ipb.ac.id*
Phone: +62813 1089 5109
ORCID: 0000-0001-9641-8820

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

The Upper Bekasi Watershed is a vital area supporting the water needs of the surrounding communities. In the context of regional development and accelerated urbanization, changes in land cover within this watershed have become a prominent challenge. The occurrence of land use changes from natural land such as forests, agricultural land, or natural vegetation to urban, residential, and industrial areas significantly impacts the local ecosystem, especially on river water quality. The transformation of land use and development is shaped by various factors, including climate, topography, soil conditions, natural disasters, and human activities affecting a specific area. Such land use change and growth can degrade water quality, increase the volume and velocity of surface water, raise the frequency of floods, double the amount of water flowing through natural forests, destroy materials, and deplete groundwater (Setyowati, 2016). To successfully plan and manage watersheds, it is essential to grasp the connection between land use and land cover change (LULC) and water quality. This knowledge is vital for identifying how non-point source pollution affects water quality (Ding *et al.*, 2016). Runoff from catchment areas introduces land use-related pollutants that influence the connection between surface water quality and changes in land use/land cover (LULC) as it flows into rivers. These contaminants can be quantitatively correlated (Rodríguez-Romero *et al.*, 2018). Many studies have shown that there is a significant correlation between land use and water quality parameters such as studies conducted by Namugize *et al.* (2018) in the uMngeni river catchment, South Africa; Zhang *et al.* (2023) in Dianchi Lake Basin, Southwest of China; Clark *et al.* (2022) in the Almirante Bay catchment, Panama. Numerous studies have integrated Geographic Information System (GIS) analysis of land use and land cover (LULC) changes with correlation analysis to examine the relationship between these two variables through the Pearson Correlation coefficient (Thomas, 2023; Kadir *et al.*, 2022; Umwali *et al.*, 2021) and Spearman correlation (Ding *et al.*, 2015). In addition, the combination of Geographic Information System based analysis and LULC changes can also be used for multivariate statistical analysis to identify the main sources of surface water quality variability using principal component analysis (PCA) (Roy *et al.*, 2024; Benkov *et al.*, 2023; Yang *et al.*, 2020), cluster analysis (Varol, 2020) or a combination of both (Nong *et al.*, 2019). To date, there has been no investigation into how alterations in land use and land cover affect river water quality on a smaller scale. In this study, Euclidean distance was used at each monitoring station to see changes in LULC and its effect on water quality at the monitoring station. Utilizing the Euclidean distance method can result in research data that is both more specific and accurate. The water quality of rivers in the Upper Bekasi Watershed was analyzed in this study using both geographical and temporal trend analysis. The results of the analysis were subsequently utilized to identify which LULC types had a significant effect on particular water quality parameters. The aims of the current study is to examine the relationship between land cover types and river water quality in the Upper Bekasi Watershed. This study has been carried out at six monitoring stations in the Cileungsi River, Cikeas River and Upper Bekasi River from 2018-2022.

MATERIALS AND METHODS

Study area

The overall area of the Upper Bekasi Watershed is ±390 square kilometers (km^2) and located in three administrative areas, namely Bogor Regency, Bekasi City, and Depok City. Within the Upper Bekasi Watershed, three significant rivers can be identified, namely the Cikeas River, the Cileungsi River, and the Upper Bekasi River. The length of the Cikeas River is 49,924 meters (m), the longest in the Upper Bekasi Watershed. In comparison, the length of the Cileungsi River and the Upper Bekasi River are 41,829 m and 10,596 m, respectively. The Bekasi River will be formed by the confluence of the Cileungsi and Cikeas rivers, eventually reaching the northern coastline of Java (Pasisingi *et al.*, 2014). The climatic condition of the Upper Bekasi Watershed is a tropical monsoon climate with relatively constant humidity and temperature. Generally, the rainy season lasts from October through April, while the dry season is observed from May until September. The average temperature in the downstream portion of the Upper Bekasi Watershed, a lowland, is around 26 degrees Celsius (^oC), while in the upstream part, which is a highland, the minimum air temperature is 20^oC. The average humidity in the downstream part is about 70 percent (%), while in the upstream

part, it is about 80%. Average annual rainfall varies between 1,000 – 3,000 millimeters (mm). The local community makes significant use of the rivers in the Upper Bekasi Watershed for a range of activities, such as irrigation, sourcing drinking water, engaging in fisheries, and additional activities. The rising population and changes in land use contribute to a yearly deterioration in river water quality, a reduction in the width of river bodies, accelerated erosion, and sediment accumulation. Consequently, these issues often lead to flooding in several areas of the Upper Bekasi Watershed, especially at the confluence of the Cikeas and Cileungsi rivers. The Upper Bekasi watershed analyzed in this study consists of six monitoring stations. In the Cileungsi River basin, there are two monitoring stations, namely Sungai Cileungsi 1 (SCL1) and Sungai Cileungsi 2 (SCL2). Likewise, in the Cikeas River and the Upper Bekasi River, there are four monitoring stations, namely Sungai Cikeas 1 (SCK1), Sungai Cikeas 2 (SCK2), Kali Bekasi Hulu 1 (KBH1) and Kali Bekasi Hulu 2 (KBH2), and a description of the sampling points can be seen in Table 1. The location of all monitoring stations in the Upper Bekasi Watershed is shown in Fig. 1.

Water quality data

Data on the water quality of the Upper Bekasi watershed is gathered from observational data by

Table 1: Description of sampling points for water sampling stations

Sample site	X-coordinate	Y-coordinate	Brief description of the site
SCL1	062713	1065527	Upper stream (Gunung Putri), where the river is polluted with industry waste.
SCL2	062251	1065741	At PDAM bridge of Kota Wisata, where the river is polluted with domestic waste, runoff etc.
SCK1	062221	1065627	At Mayor Oking, where the river is polluted with domestic waste, runoff etc.
SCK2	062850	1065204	At Nagrak, where the river is polluted with domestic waste, runoff etc.
KBH1	061650	1065859	At Kemang Pratama, where the river is polluted with domestic waste, runoff etc.
KBH2	061459	1065951	The site downstream at Bekasi dam.

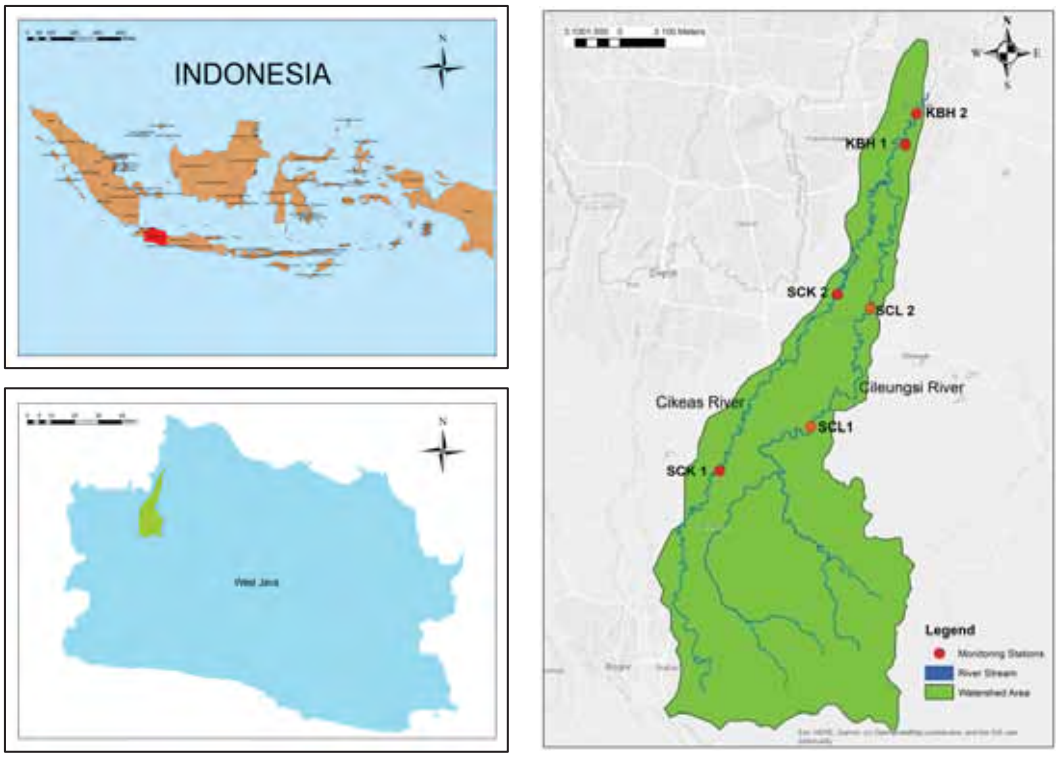


Fig. 1: Geographical location of the study area in the upper Bekasi watershed and water monitoring stations, West Java, Indonesia

Balai Besar Wilayah Sungai Ciliwung Cisadane (BBWS CC/ the River Basin Organization for Ciliwung Cisadane, the Ministry of Public Works and Housing), and Dinas Lingkungan Hidup (DLH/Environmental Agency) Bekasi City. Covering a period of four years, the Upper Bekasi Watershed water quality data set includes data from 2018 to 2022, with the exception of 2020. This was due to the Coronavirus-2019 (COVID-19) pandemic 2020, which prevented riveriwateriquality monitoring inithe Upper Bekasi Watershed. While short-term variations may not be entirely represented by sampling events, the study encompasses multiple years (2018–2022), thus delivering an extensive perspective on the trends in water quality. This temporal scope enables us to identify consistent patterns and relationships between land use changes and water quality. The sampling frequency during this period varied from two to three times yearly. Water sampling was planned to occur 2 to 4 times each year, a decision influenced by the logistical and resource challenges typically associated with large-scale field studies. Additionally, this frequency aligns with standard practices in similar studies conducted in tropical river systems, where significant trends can often be observed over longer timescales. Field sampling begins in the morning until the afternoon. Correspondingly, the measurement of river water temperature occurs concurrently with the sampling, which results in the recorded temperature being influenced by the ambient temperature during the sampling process. The sampling technique based on the scope of work is that river water quality sampling is carried out momentarily, according to the specified time. For each location, a composite sampling is carried out (mixing locations on both banks of the river and the middle, according to Standard National Indonesia (SNI): 8995: 2021. The quantity of samples collected for both field and laboratory analysis is determined by the nature of the examination being conducted. To examine the physical and chemical properties of water, approximately 3 liters are required. Sampling points are chosen based on activities that may contribute to river water pollution, including both industrial and residential practices. The observed parameters are: 1) Physics parameters: T, total dissolved solids (TDS), total suspended solids (TSS). 2) Chemical parameters: potential of hydrogen (pH), biochemical oxygen demand (BOD), chemical oxygen demand (COD), DO, nitrate (NO_3), nitrite (NO_2), PO_4, iron (Fe), cobalt (Co), zinc (Zn), copper (Cu). 3). Biological parameters: Fecal coliform (FC). The measurement of these parameters is categorized into two conditions: in situ measurements and laboratory analyses. In situ sampling was conducted using direct measurement techniques. pH and temperature samples are measured directly, while other parameters are measured through laboratory tests. Additionally, all chemical, physical, and biological characteristics were sampled using approved standard procedures by KAN No.LP-195-IDN and analyzed following international standards in an International Organization for Standardization (ISO 9001) accredited testing laboratory.

LULC information

Several public and private organizations provided the historical LULC maps used in this investigation. To ascertain the percentage of each LULC class in the Upper Bekasi Watershed, the maps were processed using Geographic Information System (ArcGIS Pro) to correlate the land cover classifications from different sources.

Statistical analysis

Descriptive statistical methods were used to determine the Mean, Standard error (SE), Median, Standard deviation, Skewness, Kurtosis, Range, Minimum and Maximum of river water quality at different periods, as seen in Table 2. In this study, the standards for river water quality are aligned with Government Regulation Number 22 of 2021, which pertains to the Implementation of Environmental Protection and Management, specifically detailed in Appendix 6. In the Upper Bekasi Watershed, encompassing the Cileungsi River, Cikeas River, and Bekasi River, the water quality is classified as class 2.

Following the approach of Giao *et al.* (2021), the Pearson correlation was conducted to ascertain whether the water quality variable, which was the dependent variable, and the LULC variable, which was deemed the independent variable, had a linear relationship. Utilizing the Pearson correlation coefficient through SPSS-25 can enhance our understanding of the relationship between two variables, clarifying whether their association is positive, negative, or absent. Based on the Pearson correlation coefficient, the relationship between two variables is considered very strong, strong,

Table 2: Summary of water quality in Upper Bekasi Watershed from six monitoring stations 2018–2022

Parameter	T	pH	TDS	TSS	BOD	COD	DO	NO_3	NO_2	PO_4	Fe	Co	Zn	Cu	Fecal coliform (FC)
unit	°C		Milligram per liter (mg/L)	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	Most probable number (MPN) /100mL
Mean	28.57	7.06	176.13	128.82	10.67	31.40	3.57	0.915	0.069	0.474	0.139	0.009	0.028	0.026	29899.68
Standard error	0.16	0.06	8.68	56.14	1.07	2.85	0.15	0.084	0.008	0.032	0.029	0.001	0.003	0.003	6973.06
Median	28.90	7.00	160.00	38.00	8.00	23.90	4.00	0.790	0.050	0.500	0.030	0.010	0.020	0.015	10000.00
Standard deviation	1.51	0.55	80.95	523.65	9.98	26.62	1.40	0.786	0.073	0.299	0.270	0.009	0.024	0.027	65040.34
Skewness	-0.30	0.16	0.72	8.79	3.68	2.85	0.14	1.828	1.958	0.123	3.628	2.395	0.985	0.705	6.02
Kurtosis	0.71	-0.06	-0.01	80.00	17.95	11.87	0.16	6.010	5.264	-0.93	15.455	6.100	-0.17	-1.31	43.42
Range	7.90	2.70	352.00	4858.00	70.91	177.95	6.71	4.756	0.398	1.232	1.712	0.039	0.099	0.069	533999.00
Minimum	24.80	5.60	59.00	2.00	2.09	5.05	0.50	0.064	0.002	0.018	0.008	0.001	0.001	0.001	1.00
Maximum	32.70	8.30	411.00	4860.00	73.00	183.00	7.21	4.820	0.400	1.250	1.720	0.040	0.100	0.070	534000.00
Quality standard (class 2)	±3°C	6.0-9.0	1000.00	50.00	3.00	25.00	Min. 4	10.000	0.060	0.200	0.000	0.200	0.050	0.020	1000.00

Table 3: LULC classification

LULC type	Code
Build up area	BA
Industry	IN
Agriculture	AG
Forest	FO
Open land	OL

moderately strong, low and very low depending on whether the absolute value of r is 1-0.80, 0.799-0.6, 0.599-0.40, 0.399-0.20, and 0.199-0.00, respectively. An analysis was conducted on the annual average concentrations of various water quality parameters at each monitoring station for the years 2018, 2019, 2021, and 2022, followed by a correlation with the LULC information from those same years. PCA was used to determine the main water parameters in the data set's variation. This technique facilitates the minimization of baseline parameters that do not substantially influence data variability, leading to the development of a new set of parameters referred to as key components or factors (PC). PCA was applied to the dataset to identify the most representative water quality parameters that better explain the sources of variance (Paná *et al.*, 2024). The eigenvalue associated with each factor is utilized to determine the principal components. A higher eigenvalue indicates a greater contribution to explaining the variability within the original dataset. Principal components extracted from the analysis to have eigenvalues greater than 1 to be further analyzed. The research employed the varimax rotation technique, leading to the identification of varifactors (VFs) that elucidate the water quality parameters most significantly influencing the variability observed in the water quality data. The validity of the PCA results was evaluated with the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity. High values close to 1.0 in the KMO test and small values (less than 0.05 of the significance level) in Bartlett's test indicate that PCA might be helpful to apply to the water quality data (Pratama *et al.*, 2020). This study employs Pearson correlation and PCA to reveal important associations between changes in LULC and various water quality parameters. This dual statistical approach not only strengthens the findings but also identifies key pollution drivers and their specific impacts on water quality.

Land use and land cover reclassification

In contrast to the prevalent studies that focus on the influence of LULC changes on water quality across extensive watershed or sub-watershed areas, this study utilizes a Euclidean distance-based approach. This method allows a more localized and precise correlation between LULC changes and water quality parameters at specific monitoring stations. The study involved the calculation of the proportion of land use types contributing to the sampling location through the delineation of Euclidean distance from each of the six monitoring stations. Euclidean distance was determined along 500 m at the monitoring station buffer (left and right of the monitoring station) and 1 kilometers (km) upstream at each monitoring station. The Geospatial Information Agency provided the land use data from 2018 to 2022, along with the drainage network and digital elevation model (DEM) data. LULC classification was performed using the guided classification method on Landsat data. Utilizing ArcGIS Pro, the maximum likelihood classification technique assigns each pixel to the class with the highest probability or similarity, relying on the information obtained from the designated training areas. Following successful extraction, LULC was classified using the Indonesian National Standard (SNI-7645-1-2014), which classifies LULC into five cover types, as shown in Table 3.

RESULTS AND DISCUSSION

Spatial trend of upper Bekasi watershed quality

Water temperature at the six monitoring stations (SCL1, SCL2, SCK1, SCK2, KBH1 and KBH2) fluctuates greatly and there is no significant difference in the range of 24.80 - 32.70^{o}C. River water temperature fluctuations are shaped by the discharge of industrial waste and are also influenced by various weather and climate factors (Wiriani *et al.*, 2018). While temperature itself does not have a direct impact on

health, it plays a significant role in the activity of microorganisms, the equilibrium of chemicals, and the increased solubility of different compounds. TDS is the portion of organic and non-organic solids that are able to pass through filters that have pores ≤2 micrometers in size (Butler and Ford, 2018). Based on Fig. 2, it can be seen that the TDS concentration at stations SCK1 and SCK 2 is the lowest compared to the other four monitoring stations, but the TDS concentration at all monitoring stations is remaining below the river water quality standard for class 2 referring to Peraturan Pemerintah (PP) No. 22 of 2021 which is 1000 mg/L. Syawal *et al.* (2016) indicated that elevated levels of organic matter contamination are associated with low total dissolved solids (TDS), suggesting that this phenomenon occurs due to the precipitation of dissolved minerals or their transformation into colloids. The concentrations of TSS, BOD and COD in this study were found to be very high and very significant compared to the average concentrations at other monitoring stations. At SCK2 there are large concentrations of TSS of 4860.00 mg/L, BOD of 73.00 mg/L and COD of 183.00 mg/L. This SCK2 monitoring station is the downstream part of the Cikeas River which is in the Upper Bekasi Watershed. Water quality in the Cikeas River is strongly influenced by anthropogenic activities in the form of settlements and housing complexes along the Cikeas River (Effendi *et al.*, 2021). The introduction of organic matter from restaurant activities, agricultural

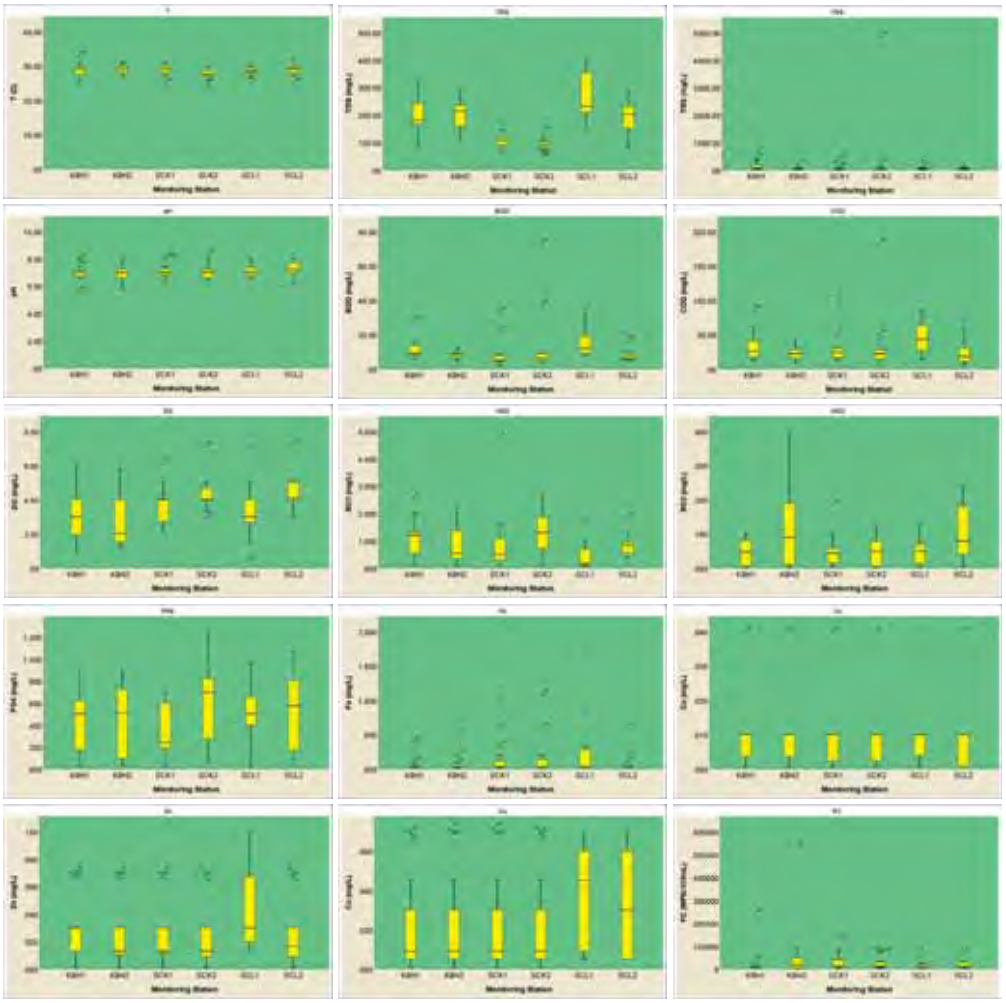


Fig. 2: The spatial trend of water quality in upper Bekasi Watershed

practices, and plantation operations may lead to elevated TSS, BOD, and COD levels in the Cikeas River. Residential settlements are the largest contributor of waste and increase organic matter to the river (Supardi *et al.*, 2017). Furthermore, elevated levels of organic matter in river water can stimulate microbial activity, leading to the breakdown of this matter into organic acid compounds through both aerobic and anaerobic processes. This decomposition can result in the production of unpleasant gases such as methane (CH4), ammonia (NH3), and hydrogen sulfide (H2S) (Ariani *et al.*, 2021). The pH level of river waters in the Upper Bekasi Watershed fluctuates in the range of 5.60-8.30 where generally the river pH ranges from 4-9 (Siahaan *et al.*, 2011). The pH of river water can be affected by rainfall and waste water entering the waters (Ramadhawati *et al.*, 2021). Supriatin *et al.* (2017) indicated that increased rainfall correlates with a decrease in the pH of rainwater, making it more acidic. This phenomenon occurs because heavy rainfall effectively removes airborne pollutants, such as sulfates and nitrates, which in turn influences the pH levels of the rainwater. DO is an importantiparameter for the survival of all aquatic organisms (Yaakub *et al.*, 2018). The DO concentration in the waters of the Upper Bekasi watershed fluctuates in the range of 0.50-7.10 mg/L. The concentration of DO is influenced by several factors, including water temperature, hydrometeorological conditions, and the rates of biological processes such as respiration, photosynthesis, and the decomposition of organic matter (Rajwa-Kuligiewicz *et al.*, 2015). NO_3 concentration was found to be 0.064-4.820 mg/L and remaining below the river water quality requirement for class 2 set at 10 mg/L. Water temperature, precipitation, and discharge levels all play a significant role in determining the distribution of NO3 concentration (Sutrisno *et al.*, 2018). Point sources of pollution such as industrial and domestic wastewater and the heavy use of fertilizers in agriculture can cause an increase in NO_3 in river water (Zhang *et al.*, 2021). NO_2 concentrations at all monitoring stations exceeded the river water quality standard ofi0.06 mg/L.

Nitrogen in NO_2 is in a relatively unstable oxidized form and NO_2 has a high level of toxicity for living things so that it can cause methaemoglobinaemia, cyanosis and asphyxia at higher concentrations (Sato *et al.*, 2018). The detection of NO_2 in river water indicates the active biological decomposition of organic material, which is associated with significantly low levels of DO (Effendi, 2003). Among the chemical factors influencing the quality of water is the PO_4 parameter. The concentration of PO_4 in the waters of the Upper Bekasi Watershed is in the range of 0.018-1.250 mg/L. The entry of PO_4 into a water body naturally can be caused through the process of rock weathering into PO_4 minerals (Wulandari *et al.*, 2021), agricultural waste in the form of phosphorus-based inorganic fertilizers (Patricia *et al.*, 2018) as well as the application of detergents (Wiriani *et al.*, 2018). The presence of the PO4 parameter is regarded as toxic because it includes nitrogen, a substance that can encourage the growth of algae, resulting in algal blooms (Karima and Kaswanto, 2017). The heavy metal parameters studied in this study are Fe, Co, Zn and Cu where these four metals are pollutants in water bodies. The presence of Fe metal is derived from the weathered rocks and crustal materials. In contrast, Co and Zn metals primarily originate from human activities, including industrial waste, coal combustion, and vehicle emissions. Additionally, Co metal can be sourced from both anthropogenic activities and natural occurrences (Chai *et al.*, 2021). When seen in Fig. 2, the highest average heavy metal concentration is at SCL1. Station SCL1 is the upstream part of the Cileungsi River where there are many industries around it that affect the river Cileungsi's water quality (Effendi *et al.*, 2021The extensive mining operations in the upper reaches of the Cileungsi River also play a significant role in this influence. The heavy metals Fe and Zn found in aquatic ecosystems can accumulate in water hyacinth plants and goldfish (Riani *et al.*, 2024) and Pennahia argentata is one of the fish commonly consumed in Southeast Asia (Takarina *et al.*, 2023). The European Environmental Agency has identified FCias as a key microbiological indicator for assessing the quality of drinking water (Zhang *et al.*, 2020). *Escherichia coli* (*E. coli)* bacteria are FC bacteria that are used as sanitation parameters in general because *E. coli* bacteria are indicators of fecal pollution and pathogenic bacteria in food and water and detection is easier and cheaper than detection of pathogenic bacteria. It is well-documented that specific strains of E. coli bacteria can be pathogenic, exhibiting symptoms that are akin to those of cholera and shigellosis (Soewandita and Sudiana, 2018). FC was found at all monitoring stations in the waters of

the Upper Bekasi Watershed and exceeded the class 2 river water quality standard set at 1,000 MPN/100 mL. The highest FC concentrations were in KBH1 and KBH2 where KBH1 is upstream of the Bekasi River, while KBH2 is downstream of the Bekasi River. The Bekasi River originates from the merging of the Cileungsi River and Cikeas River. The Bekasi River flows through low-lying areas, surrounded by numerous residential communities and housing developments. Based on the results of Li *et al.* (2022) research, urban domestic waste and agricultural activities are the main sources of FC pollution in the river.

Temporal Trend of Upper Bekasi Watershed Quality

Based on the temporal trend analysis from 2018-2022, there are several parameters with increasing concentration trends, namely NO_3, NO_2, PO_4, Cu and FC as presented in Fig. 3. The parameters exhibiting a declining concentration trend include DO, whereas the other parameters display fluctuations on an annual basis. The water temperature in the Upper Bekasi Watershed is affected by the climate during river water sampling. The study area experiences only two distinct seasons: the dry season and the rainy season. Consequently, water temperature readings taken during the dry season tend to be higher. Conversely, when sampling is done during the rainy season, the water temperature becomes lower. Annually, there is a reduction in the concentration of dissolved oxygen within the waters of the Upper Bekasi Watershed. Rajesh and Rehana (2022) stated that the ecosystem's health in river water bodies is determined by the proportion of DO, so this needs to be a concern in carrying out watershed management. COD, BOD and TSS parameters in the waters fluctuate annually, indicating the consistency of domestic and industrial wastewater entering the waters. The concentrations of NO3, NO2, and PO4 have risen annually, attributed to the growing levels of organic matter in the water. This increase in organic content subsequently elevates the amounts of nitrogen, PO4, and other inorganic nutrients, which are recycled to nourish phytoplankton, potentially resulting in eutrophication in aquatic environments. The overflow of river water from the mainland that transports nutrients and organic waste discharges due to household, agricultural and industrial activities is an organic matter source entering the waterways. From 2018 to 2022, there was an increase in the concentration of copper in the waters of the Upper Bekasi Watershed. Cu metal is a heavy metal that is not biodegradable and tends to accumulate in living organisms and is carcinogenic. Cu metal is a micronutrient that, along with other proteins and enzymes, is crucial for the creation of bones. However, at larger doses, Cu metal can have extremely harmful effects (Ding *et al.*, 2014). The sources of Cu metal pollution are diverse and include waste from several industrial sectors, such as metal cleaning and coating baths, fertilizer manufacturing, paperboard production, paint and pigment industries, mining, smelting, petroleum refining, brass rinsing, wood pulp production, and the fabrication of printed circuit boards (Arbabi and Golshani, 2016).

FC concentrations from 2018-2022 also increased. The lowest FC concentration was 1.00 MPN/100mL and the highest was 534,000.00 MPN/100mL. The occurrence of FC in the Upper Bekasi watershed raises significant concerns, particularly since the average concentration at all monitoring locations is above the acceptable limits for class 2 river water quality. In addition, exposure to FC bacteria directly increases the health risk for residents in the Upper Bekasi watershed. A time series is a collection of data points that are usually measured at regular intervals between one another (Parmar and Bhardwaj, 2014). The field of time series analysis encompasses various methods aimed at evaluating time-ordered data to uncover valuable statistics and attributes, while also facilitating the forecasting of future events grounded in previously observed data, allowing for the anticipation of data points before they are recorded. The time series model reflects that observations are more closely related together in time than observations further apart. The time series for all monitoring stations for river water quality parameters in 2018-2022 is presented in Fig. 4.

The findings of the study indicated that seasonal fluctuations affected the time series data at multiple monitoring stations concerning water quality parameters. This time series can be seen in the time series of T, TDS and pH parameters where the trend in February the measured values were lower than in other months, while in August, the T, TDS and pH values were higher. The analysis of the time series for TSS, BOD, and COD parameters revealed a stable trend. There was no fluctuation, but there was a similarity in the presence of very high pollution by

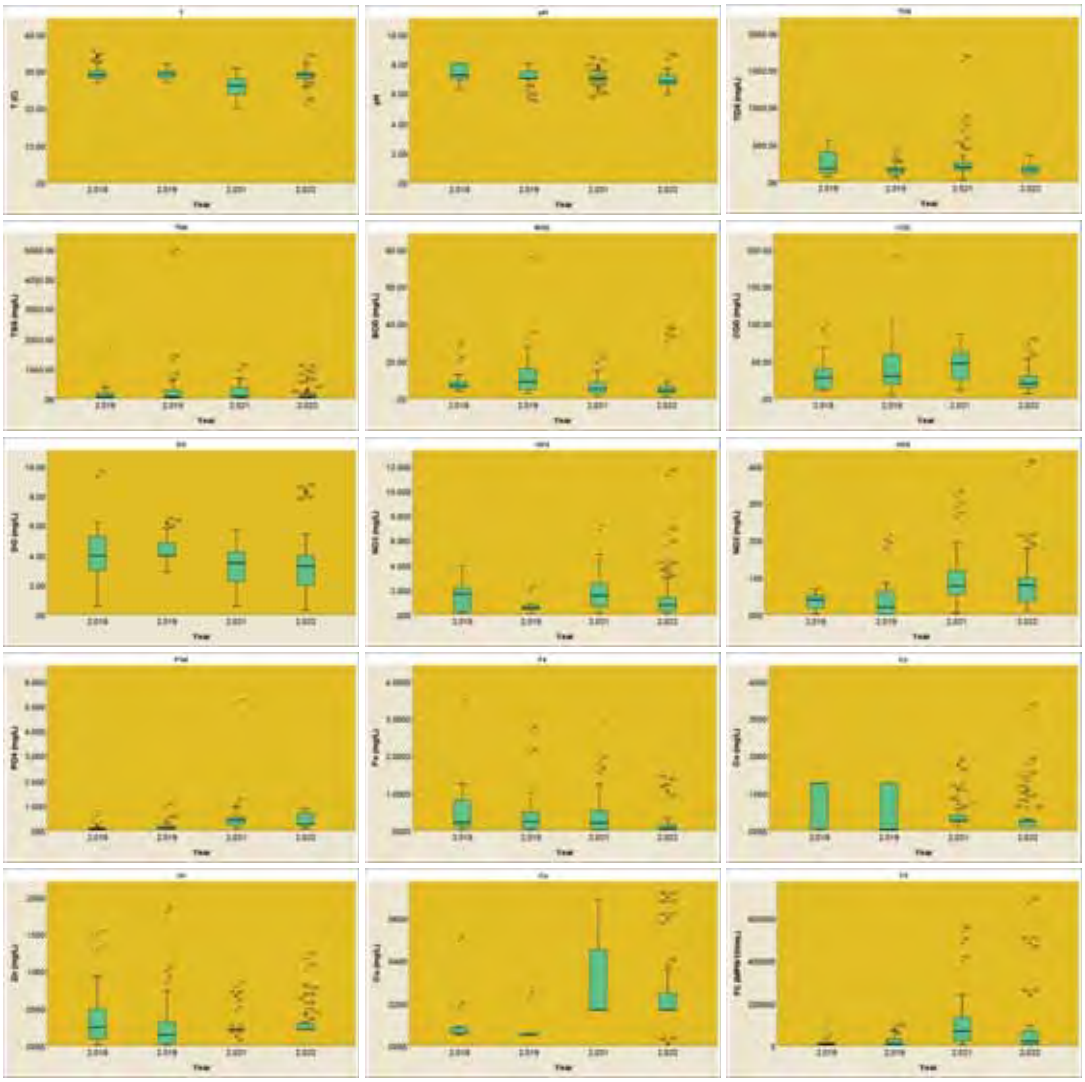


Fig. 3: Temporal trend of the water quality in Upper Bekasi Watershed

the three parameters in February 2019 at SCK2. The NO_3, NO_2, and FC parameters have a time series that fluctuates over time and at the same time, there was very significant pollution in August 2021. The time series data for heavy metals, including Co, Zn, and Cu, revealed elevated pollutant levels in February 2021, which subsequently decreased in 2022. Unlike the time series for the DO and PO_4 parameters, which have irregular variations, the time series for the Fe parameter obtained a high concentration in February 2019. Then, they stagnated from February 2021 to November 2022. In this study, there was no water quality in the Upper Bekasi watershed in 2020 due to the COVID-19 pandemic. The decision to exclude data from 2020 was influenced by the logistical difficulties presented by the COVID-19 pandemic, which limited field sampling efforts. It is possible that 2020 exhibited distinct pollution patterns as a result of decreased industrial and human activities during the lockdown periods. However, as this study focuses on long-term trends (2018–2022) and the relationship between land use changes and water quality, the absence of one year of data is unlikely to affect the robustness of the observed correlations significantly. In order to limit bias, the analysis focuses on the available multi-year data, omitting 2020, to revea consistent trends.

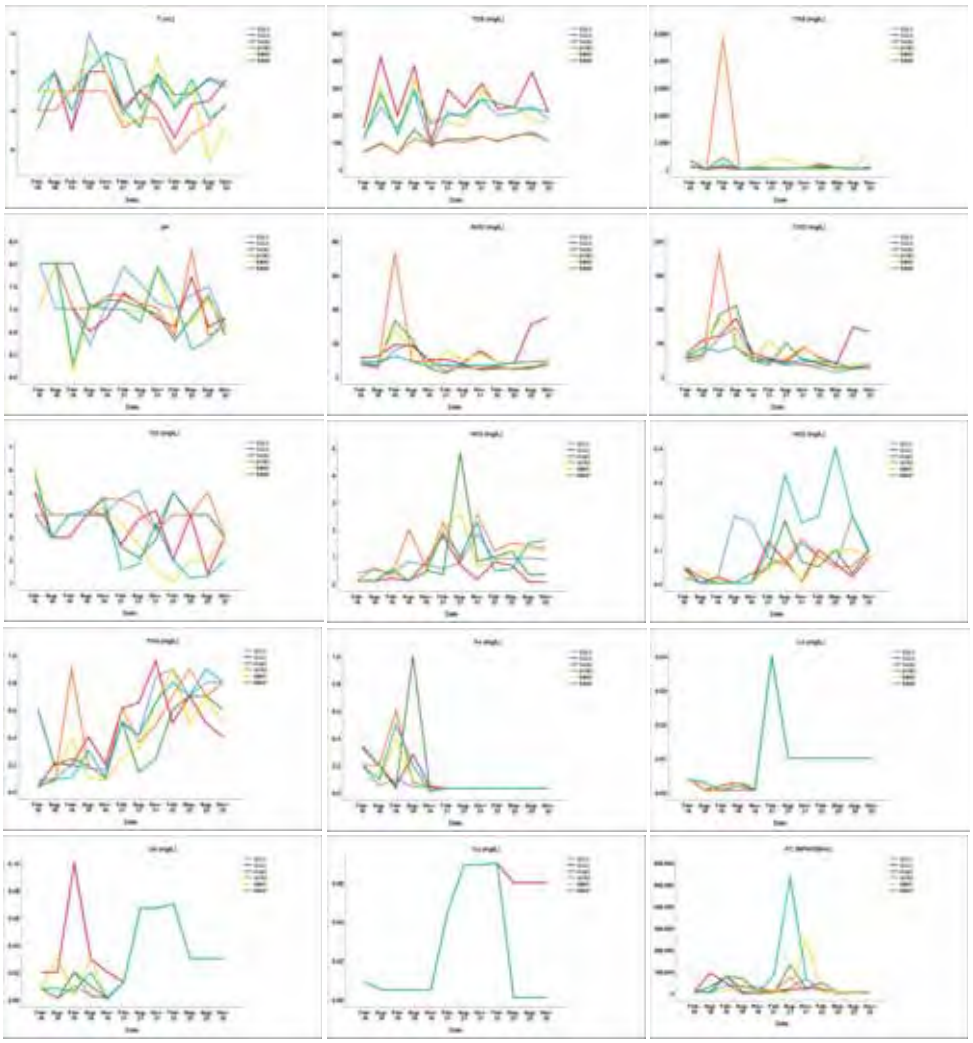


Fig. 4: Time series of water quality parameters at six monitoring station of the Upper Bekasi Watershed

LULC Changes

The categorization of LULC in the Upper Bekasi Watershed was carried out alongside the water quality monitoring efforts during the period of 2018 to 2022, with the exception of 2020. The LULC classification in the Upper Bekasi Watershed consists of five classes, namely build-up area (BA), industry (IN), agriculture (AG), forest (FO), and open land (OL) with the distribution of LULC shown in Table 4, while Fig. 5 illustrates the LULC classification results based on the Euclidean distance from each water monitoring station in the Upper Bekasi Watershed. The main land cover in the entire Upper Bekasi Watershed based on Table 4 is BA with an area of 37.46 - 47.84%, AG with an area of 13.16 - 36.18% and FO with an area of 13.38 - 29.89% of the total area of the Upper Bekasi Watershed.

The BA class shows an increase in area in the 2018-2022 period of 10.38% of the total area of the Upper Bekasi Watershed. The development of constructed environments results in a higher prevalence of impervious surfaces, including streets, building tops, and paved areas. These surfaces prevent water infiltration into the soil, leading to increased surface runoff. Meanwhile, the negative trend is shown by the AG and OL classes where there was a decrease in area by 11.57% and 4.59% during the 2018-2022 period. Changes in land use, such as the conversion of agricultural and open land into urban developments or industrial zones, can lead to a

Table 4: Distribution of LULC changes in DAS upper Bekasi from 2018 to 2022

		2018		2019		2021		2022		
		Area	Area	Area	Area	Area	Area	Area	Area	% of change
No	LULC Class	Km^2	%	Km^2	%	Km^2	%	Km^2	%	2018-2022
1	Build up Area	147.1	37.46	159.9	40.71	172.6	44.00	187.8	47.84	10.38
2	Industry	7.2	1.84	8.5	2.16	8.1	2.06	11.1	2.81	0.97
3	Agriculture	106.6	27.13	142.1	36.18	51.6	13.16	61.1	15.56	-11.57
4	Forest	98.5	25.09	52.5	13.38	98.0	24.98	117.4	29.89	4.80
5	Open Land	33.3	8.49	29.7	7.57	62.4	15.80	15.3	3.90	-4.59
	Total	393	100.00	393	100.00	393	100.00	393	100.00	

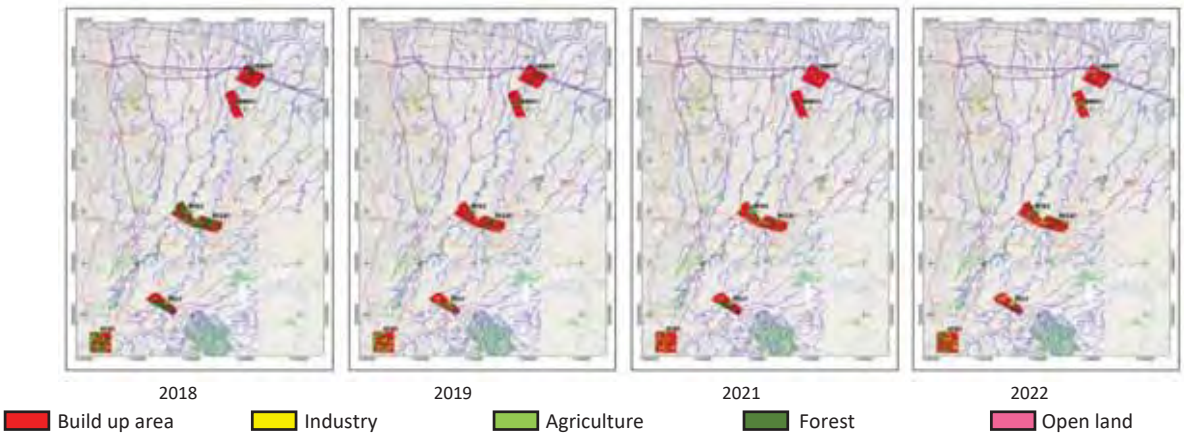


Fig. 5: LULC classification of the Upper Bekasi watershed in 2018–2022

decrease in available area Kaswanto *et al.* (2021) stated that population size and population density are some of the factors driving changes in land cover. As depicted in Fig. 6, the area of each land cover class obtained from the Euclidean distance is subsequently expressed as a percentage of the total area for each class. The land cover class determined is the same as the land cover class studied in the Upper Bekasi Watershed, namely five classes with a period of 2018-2022 (excluding 2020). Based on the percentage of land use distribution in Fig. 6, KBH1 and KBH2 stations have the largest built-up area compared to other monitoring stations. This situation arises from the fact that the two stations are positioned downstream of the Cileungsi and Cikeas Rivers, in an area with a relatively level topography. Consequently, the vicinity is largely occupied by residential areas, housing complexes, and business establishments. In addition, the Upper Bekasi River is also located in an urban area so that changes in land cover tend to increase built-up land as a consequence of regional development (Husodo *et al.*, 2021).

The largest industrial land use class is in SCL1 in the 2022 period of 9.29% of the Euclidean distance area of SCL1 station. SCL1 station is located in the upstream part of the Cileungsi River where there is a dense industrial area around the Cibinong Cement Factory, Holcim Cement Factory and the Branta-Mulia industrial area (Djamudin *et al.*, 2012). A significant decrease in land cover area occurred in forest land where in 2018 the forest area ranged from 10.37 - 36.80%, while in 2022 the forest area was only in the range of 0.72 - 12.68%. Acting as natural shields, forests diminish the speed of runoff, cleanse pollutants, and help maintain river temperatures through their shading effects. Deforestation in upstream areas undermines these ecological services, leading to heightened pollutant concentrations and thermal stress within aquatic environments. Changes in land cover can be caused by changes in the function of forest land into built-up land, open land and agricultural land that can

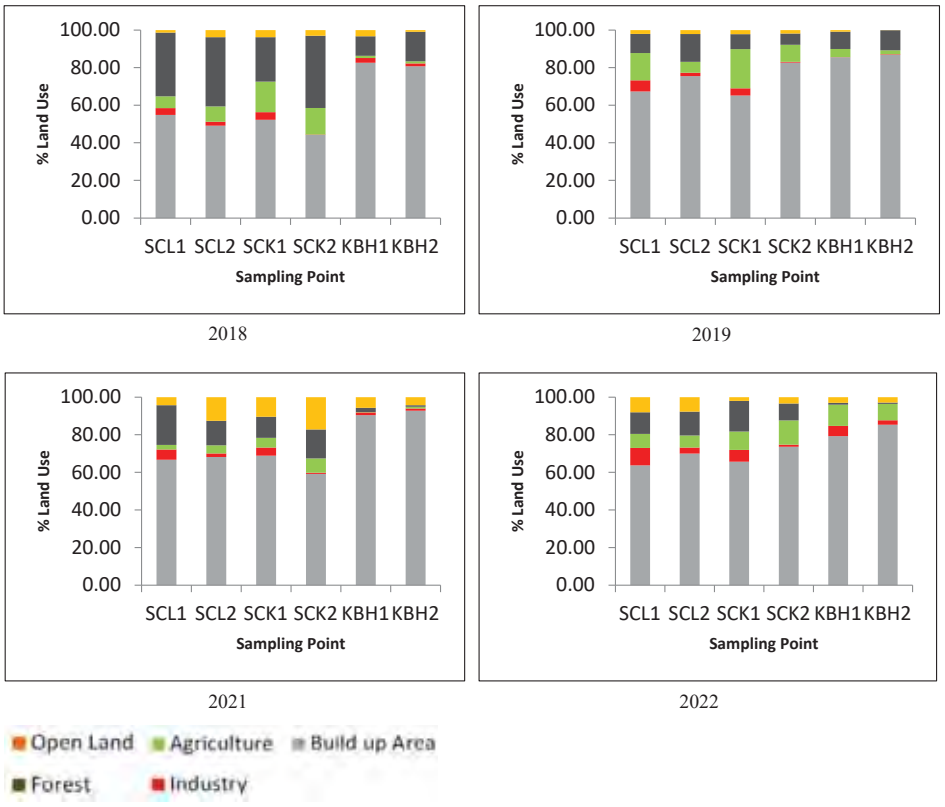


Fig. 6: Percentage of land use distribution in six sampling points for 2018-2022

be used directly for anthropogenic activities.

Correlation analysis between the LULC changes and water quality

The correlation between LULC changes and water quality in the Upper Bekasi Watershed was quantified using the Pearson correlation coefficient. The correlation between annual LULC changes in the six Euclidean distance areas and each water quality parameter was examined, and the results are detailed in Table 5. In the Cileungsi River waters, there are two monitoring stations, namely SCL1 and SCL2. At both stations, a very strong correlation was obtained between BA and NO_3 and Fe parameters of 0.974 and -0.902. Then there was also a strong and significant correlation between AG and TDS and COD parameters at SCL1 of -0.937 and 0.984, while SCL2 had no significant correlation with other parameters. The robust connection between AG and COD is probably a result of agrochemical usage, with substances like fertilizers, pesticides, fungicides, and herbicides infiltrating agricultural areas (Setyowati, 2016). For this reason, the nutrient management plans needed to optimize fertilizer application, reducing excess nutrient runoff into water bodies. A very strong correlation was also seen between FO and the parameters pH, NO_2 and Fe with coefficient values of 0.911, -0.907 and 0.956 respectively. This study includes two monitoring stations, SCK1 and SCK2, located along the flow of the Cikeas River. The Pearson correlation coefficient obtained a very strong correlation between BA and TDS at SCK1, while at SCK2 there was no significant relationship between BA and other parameters.

In line with Rahman *et al.* (2014) research, it was found thatithe type of residential land use has a positive relationship with TDS, where this relationship shows that the larger proportion of settlements has the potential to increase TDS values logarithmically. In SCK1, a very strong negative relationship was obtained between AG and the parameters NO_2, Co, and Zn with coefficient values of -1,000, -0.954, and -0.912. This is consistent with the study conducted by Putri *et al.* (2021), which demonstrates a negative correlation between the NO2 parameter and the extent of

Table 5: Pearson correlation coefficients between the LULC and water quality parameters

Parameter	SCL1			SCL2			SCK1			SCK2			KBH1			KBH2		
	BA	AG	FO	BA	AG	FO	BA	AG	FO	BA	AG	FO	BA	AG	FO	BA	AG	FO
T	-0.714	0.291	0.535	0.474	-0.390	-0.435	0.846	0.034	**-.989***	0.305	-0.216	-0.075	0.377	-0.516	0.829	-0.583	-0.437	**.922***
pH	-0.671	-0.42	**.911***	-0.371	0.229	0.523	-0.681	0.718	0.126	-0.830	0.367	**.929***	0.205	-0.621	0.098	-0.425	-0.601	0.590
TDS	-0.054	**-.937***	0.863	0.526	-0.588	-0.512	**.914***	-0.702	-0.495	0.386	-0.226	-0.610	0.388	-0.083	0.317	0.510	0.629	**-.951***
TSS	-0.819	-0.26	0.796	-0.738	0.793	0.676	0.098	0.834	-0.569	0.708	-0.392	-0.521	0.402	-0.026	-0.869	-0.398	0.035	0.539
BOD	-0.131	0.428	-0.804	0.200	-0.121	-0.149	0.013	0.865	-0.538	0.689	-0.364	-0.493	0.671	-0.380	0.308	-0.852	0.097	0.774
COD	-0.380	**.984***	-0.620	0.069	-0.032	0.071	0.083	0.738	-0.650	0.598	-0.411	-0.412	0.658	-0.540	0.533	-0.468	-0.715	**.948***
DO	-0.170	0.03	0.649	-0.494	0.348	0.748	-0.154	0.727	0.014	0.628	-0.751	-0.576	0.061	-0.555	**.994***	-0.489	-0.673	**.951***
NO_3	**.974***	-0.44	-0.161	0.773	-0.802	-0.766	0.683	-0.851	-0.418	0.332	-0.711	-0.628	0.463	0.039	-0.890	0.857	0.149	**-.913***
NO_2	0.466	-0.78	0.033	0.819	-0.718	**-.907***	0.490	**-1.000***	0.012	-0.133	-0.216	-0.176	-0.463	0.712	-0.868	0.539	0.570	**-.949***
PO_4	0.860	-0.55	-0.219	0.518	-0.498	-0.682	-0.026	-0.418	0.566	0.661	-0.226	-0.799	-0.234	0.714	**-.952***	0.434	0.767	**-.936***
Fe	-0.797	0.158	0.626	**-.902***	0.874	**.956***	-0.527	**.956***	-0.054	0.028	0.146	0.256	0.043	-0.174	0.813	-0.395	-0.430	0.803
Co	0.812	-0.73	0.047	0.563	-0.653	-0.457	0.635	**-.954***	-0.237	-0.112	-0.512	-0.225	0.544	-0.157	-0.799	0.749	-0.002	-0.783
Zn	0.866	0.258	-0.711	0.613	-0.657	-0.623	0.778	**-.912***	-0.302	0.068	-0.366	-0.377	0.240	0.086	**-.901***	0.717	0.347	**-.950***
Cu	0.576	-0.62	-0.193	0.504	-0.528	-0.585	0.570	-0.876	-0.297	-0.189	-0.631	-0.145	0.709	-0.360	-0.653	0.846	-0.208	-0.698
FC	-0.686	-0.13	0.829	0.719	-0.766	-0.437	0.568	0.003	-0.877	0.896	-0.760	**-.961***	**.907***	-0.592	-0.392	0.882	-0.438	-0.536

*Statistically significant

Table 6: Three extracted VFs from the 6 parameters of water quality

Parameter	VF1	VF2	VF3
TSS	0.804		
BOD	0.971		
COD	0.929		
TDS		0.923	
pH			0.751
FC			0.722
Eigenvalue	2.491	1.102	1.091
% of variance	41.510	18.367	18.181
Cumulative %	41.510	59.877	78.057

agricultural land. In other words, larger agricultural areas are associated with lower concentrations of NO2 in aquatic environments. It is assumed that the conversion of NO_2 to NO_3 in the nitrogen cycle is rapid. However, at this monitoring station, AG has a very strong positive correlation with the Fe parameter. In addition, in the Cikeas River waters, a very strong negative relationship was found between FO and the temperature parameter of -0.989 and the FC parameter of -0.961. In a negative relationship, an increase in one variable leads to a reduction in the other. Consequently, a larger forest area in SCK1 correlates with a lower temperature of the river water. Vegetation cover in forested regions plays a crucial role in lessening the amount of sunlight that penetrates to the river's surface, thereby contributing to a decrease in the temperature of the river water. In line with thestudy by Suharyanto *et al.* (2023), if the vegetation index decreases, the built-up index increases, and land surface temperature also increases. Vice versa, if the vegetation index increases, the built-up index decreases, and the land surface temperature also decreases. There is a negative correlation between the FC parameter and FO, suggesting that larger forest areas correspond to a reduced presence of FC in the river water. This is because the wider the forest area means a low population density and population, so that the number of FC bacteria from human feces/ excrement entering the waters is getting smaller. The Upper Bekasi River is the downstream of the Cileungsi River and the Cikeas River. Along the Upper Bekasi River, there are two monitoring stations in this study, namely KBH1 and KBH2. There is a very strongipositiveicorrelationiof 0.907 between BA and the FC parameter. A large concentration of residential areas, housing complexes, and commercial buildings can be found near the Upper Bekasi River, contributing to a notably high population in the vicinity. Urbanization increases population density, which correlates with higher volumes of domestic waste, including human feces. When sanitation systems are inadequate, these wastes contribute to elevated FC levels in water bodies. In addition, many urban areas in the Upper Bekasi Watershed do not yet have a comprehensive wastewater treatment system, resulting in a lot of untreated or partially untreated domestic wastewater being discharged into rivers. Urban stormwater runoff serves as a pathway for fecal contaminants originating from multiple sources, such as human and animal waste, malfunctioning septic systems, and unregulated sanitation methods. In KBH1 and KBH2, no relationship was found between AG and other parameters. There is ainegative relationship between FO and the PO_4 and Zn parameters, namely -0.952 and -0.901 (KBH1) and -0.936 and -0.950 (KBH2). A positive relationship was also obtained at the KBH2 station between FO and the COD and DO parameters (0.948 and 0.951). Consequently, effective management of urbanized areas in the Upper Bekasi Watershed calls for specific interventions, such as upgrading wastewater treatment systems, employing green stormwater management strategies, and rehabilitating riparian zones to boost pollutant filtration. Sources of Upper Bekasi watershed pollution were identified on the basis of the PCA results. Preliminary tests, including the KMO, Bartlet test, anti-image test, and scree plot, were conducted prior to the analysis in order to determine whether the water quality data conformed to the statistical criteria. Based on the test results, 9 of the 15 river water quality monitoring parameters, namely T, DO, NO3, NO2, PO4, Fe, Co, Zn, and Cu, were not included in the PCA because the anti-image test's MSA value was more than 0.5. Thus, the remaining water quality parameters included in the PCA were TSS, BOD, COD, TDS, pH, and

FC. Table 6 shows the PCA results, extracting the three rotated principal components (VFs) and the significant loadings of the water quality parameters for each PC.

In Table 6, the variance factors extracted from the water quality data are illustrated, revealing that they represent 78.057% of the total variance in the dataset. VF1 explained 41.510% of the total variance in the water quality data and had a strong positive loading on the parameters TSS, BOD and COD. VF1 can represent organic pollutants in the waters of the Upper Bekasi Watershed. According to a study by Nascimento *et al.* (2019), PCA in the Rio do Peixe watershed, a tributary of the Rio Doce River, located in the Iron Quadrangle, extracted the main VFs and had a positive loading effect on TSS,BOD and COD. The key components were connected to both natural decay processes and waste produced by human activities in domestic settings. VF2 explained 18.367% of the total variance in the water quality data and had a positive loading effect on TDS. PC2 can represent the source of nutrient pollutants in the waters of the Upper Bekasi Watershed originating from agriculture. Surface water often receives agricultural runoff that is rich in nutrients, particularly phosphorus and nitrogen. VF3 explained 18.181% of the total variance of water quality data, having a positive loading effect on pH and FC. PC3 may represent pollutants originating from industrial wastewater for pH parameters, while FC may originate from domestic wastewater in residential areas, livestock farms and recreational areas (Camara *et al.*, 2019).

CONCLUSION

The findings of this study highlight the application of GIS-based spatiotemporal analysis in understanding the fluctuations in water quality in the Upper Bekasi River, Indonesia. Furthermore, it pinpoints the key sources that may lead to water pollution in these aquatic environments. The water quality in each river varies, as evidenced by the different pollution levels in the Cileungsi River, Cikeas River and Upper Bekasi River. The disparities in river water quality arise from various pollution sources and differing land cover and usage changes, which are not uniform across the catchment area in each river. The highest pollution in the Cikeas River was the TSS parameter of 4860.00 mg/L, BOD of 73.00 mg/L and COD of 183.00 mg/L. The quality of water in the Cikeas River is heavily affected by anthropogenic factors, particularly from the settlements and housing complexes that line its shores. The highest pollution in the Cileungsi River was found at the SCL1 monitoring station, where the concentrations of heavy metals Fe, Co, Zn and Cu were measured, which exceeded the river water quality standards. SCL1 station is located in the upstream part of the Cileungsi River, which is a dense industrial area. In the Upper Bekasi River, the highest pollution measured was the FC parameter of 534,000 MPN/100mL. Originating from the merging of the Cileungsi and Cikeas Rivers, the Bekasi River traverses lowland areas that are home to various settlements and housing developments. The water quality in the Upper Bekasi Watershed fluctuates on average yearly. However, based on the results of the study obtained in 2018-2022, there was an increase in the concentration of NO_3, NO_2, PO_4, Cu and FC every year. Parameters NO_3, NO_2, and PO_4 increased in concentration every year. The observed changes are a result of heightened organic matter presence in the water, leading to increased levels of nitrogen, PO4, and various other inorganic nutrients. This is different from the DO parameter, where there is a decrease in concentration every year based on the study results. The main land cover in the entire Bekasi Hulu watershed is BA, with an area of 37.46 – 47.84%; AG, with an area of 13.16 – 36.18%; and FO, with an area of 13.38 – 29.89% of the total area of the Bekasi Hulu watershed. The BA class shows an increase in area in the 2018-2022 period of 10.38% of the total area of the Upper Bekasi Watershed. Conversely, the AG and OL classes reflect a downward trend, experiencing a decline in their areas of 11.57% and 4.59% during the timeframe of 2018 to 2022. The decrease in area can be caused by changes in land use cover in agricultural areas and open land to built-up areas, industry or other land cover. KBH1 and KBH2 stations have the most significant built-up area compared to other monitoring stations. In 2022, the predominant industrial land use category is SCL1, accounting for 9.29% of the Euclidean distance area. A significant decrease in land cover area occurred in forest land where in 2018, the forest area ranged from 10.37 - 36.80%, while in 2022, the forest area was only in the range of 0.72 - 12.68%. The findings of the study indicated a relationship between land use practices and the quality of river water. At the SCL1 monitoring station, a very strong correlation was obtained between BA and NO_3 and Fe parameters of 0.974 and -0.902, between AG and TDS and COD parameters of -0.937 and 0.984, between FO and the parameters

pH, NO_2 and Fe with coefficient values of 0.911, -0.907 and 0.956 respectively. At the Cikeas River monitoring station, a robust correlation was found between BA and TDS. Furthermore, a pronounced negative association was observed between AG and the parameters NO_2, Co, and Zn with coefficient values of -1,000, -0.954, and -0.912 at SCK1. A very strong negative relationship was found between FO and the temperature parameter of -0.989 and the FC parameter of -0.961 at SCK2. At the monitoring station located in the upstream Bekasi River, a very strong positive correlation of 0.907 between BA and FC was obtained. A negative relationship was also obtained between FO and the PO_4 and Zn parameters, namely -0.952 and -0.901 (KBH1) and -0.936 and -0.950 (KBH2). A positive relationship was also obtained at the KBH2 station between FO and the COD and DO parameters (0.948 and 0.951). The number of PCs obtained in this study had three components: VF1 explained 41.510% had a strong relationship with TSS, BOD, and COD parameters; VF2 explained 18.367% had a relationship with TDS parameters; and VF3 explained 18.181% of the total variance had a relationship with pH and FC parameters. This study's outcomes serve as a critical reference for water quality management in the Upper Bekasi River Basin and similar regions. It will support stakeholders, especially the Government of Indonesia, in identifying appropriate intervention techniques to address wastewater pollution. Based on the findings of this study, stakeholders are encouraged to adopt stricter regulations for wastewater treatment in both urban and peri-urban settings. The formulation of nutrient management plans aimed at optimizing fertilizer use is also recommended to mitigate excess nutrient runoff into water bodies. Furthermore, it is important to initiate reforestation efforts in regions with diminished forest cover. Increasing local community awareness regarding the negative consequences of improper waste disposal on water quality is vital. Lastly, promoting collaboration among urban planners, ecologists, and policymakers will facilitate a more integrated approach to watershed management.

AUTHOR CONTRIBUTIONS

D.P. Marisi contributed to this work by conceptualizing the study, applying for funding, designing the experimental work, analyzing the data, writing the initial manuscript, and finalizing the manuscript. Suprihatin contributed to conceptualizing the study, supporting the manuscript writing, reviewing, and revising. S. Hariyadi contributed to conceptualizing the study, supporting the manuscript writing, reviewing, and revising. L.R. Kaswanto contributed to conceptualizing the study, supporting the manuscript writing, reviewing, and revising.

ACKNOWLEDGEMENT

The water quality of Upper Bekasi watershed used in this study was provided by the River Basin Organization for Ciliwung Cisadane, the Ministry of Public Works and Housing. This study, including data analysis and drafting, was funded by LPDP (Ministry of Finance, Republic of Indonesia) with funding number [KET-3915/LPDP.4/2022].

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent (part per hundred)
µm	Micrometer
AG	Agriculture
BA	Build-up area (BA
BBWS CC	Balai Besar Wilayah Sungai Ciliwung Cisadane
BOD	Biological oxygen demand
CH_4	Methane
Co	Cobalt
COD	Chemical oxygen demand
COVID-19	Coronavirus disease-2019
Cu	Copper
DEM	Digital elevation model
DLH	Dinas Lingkungan Hidup
DO	Dissolved oxygen
FC	Fecal coliform
Fe	Iron
FO	Forest
H_2S	Hydrogen sulfide
IN	Industry
ISO	International organization for standardization
KAN	Komite akreditasi nasional (National accreditation committee)
KBH	Kali Bekasi Hulu (Upper Bekasi river)
Km^2	Square kilometer
KMO	Kaiser–Meyer–Olkin (KMO)
L	Liter
LULC	Land use and land cover
m	Meter
mL	Milliliter
mm	Millimeter
MPN	Most probable number
NO_2	Nitrite
NO_3	Nitrate
^oC	The degree celcius
OL	Open land
PC	Key component or factor
PCA	Principal component analysis
pH	Potential of hydrogen
PO_4	Total phosphate
PP	Peraturan Pemerintah
SCK	Sungai cikeas (Cikeas river)
SCL	Sungai cileungsi (Cileungsi river)
SE	Standard error
SNI	Standard National Indonesia (Indonesian National Standard)
SPSS	Statistical package for the social sciences
T	Temperature
TDS	Total dissolved solids
TSS	Total suspended solids
VFs	Varifactors
Zn	Zinc

REFERENCES

Arbabi, M.; Golshani, N., (2016). Removal of copper ions Cu (II) from industrial wastewater: A review of removal methods. Int. J. Epidemiol. Res., 3(3): 283–293 **(11 pages)**.

Ariani, F.; Effendi, H.; Suprihatin, S., (2021). Analisis beban dan tingkat pencemaran di Perairan Dumai, Provinsi Riau. Jurnal Pengelolaan Lingkungan Berkelanjutan. J. Environ. Sustainable Manage., 4(2): 486–497 **(12 pages)**.

Benkov, I.; Varbanov, M.; Venelinov, T.; Tsakovski, S., (2023). Principal component analysis and the water quality index—A powerful tool for surface water quality assessment: A case study on struma river catchment, Bulgaria. Water. 15(1961): 1-16 **(16 pages)**.

Butler, B.A.; Ford, R.G., (2018). Evaluating relationships between total dissolved solids (TDS) and total suspended solids (TSS) in a mining-influenced watershed. Mine Water Environ., 37(1): 18–30 **(13 pages)**.

Camara, M.; Jamil, N.R.; Abdullah, A.F., (2019). Impact of land uses on water quality in Malaysia: a review. Ecol. Processes. 8(10):1-10 **(10 pages)**.

Chai, N.; Yi, X.; Xiao, J.; Liu, T.; Liu, Y.; Deng, L., (2021). Spatiotemporal variations, sources, water quality and health risk assessment of trace elements in the Fen River. Sci. Total Environ., 757: 1-11 **(11 pages)**.

Clark, K.E.; Bravo, V.D.; Giddings, S.N.; Davis, K.A.; Pawlak, G.; Torres, M.A., (2022). Land use and land cover shape river water quality at a continental caribbean land-ocean interface. Front. Water. 4:1-19 **(19 pages).**

Ding, J.; Jiang, Y.; Fu, L.; Liu, Q.; Peng, Q.; Kang, M., (2015). Impacts of land use on surface water quality in a subtropical River Basin: A Case Study of the Dongjiang River Basin, Southeastern China. Water. 7:4427-4445 **(19 pages)**.

Ding, J.; Jiang, Y.; Liu, Q.; Hou, Z.; Liao, J.; Fu, L., (2016). Influences of the land use pattern on water quality in low-order streams of the Dongjiang River Basin, China: A multi-scale analysis. Sci. Total Environ., 551-552(19): 205-216 **(12 pages).**

Ding, Y.; Shen, S.Z.; Sun, H.; Sun, K.; Liu, F., (2014). Synthesis of l-glutathione-capped-ZnSe quantum dots for the sensitive and selective determination of copper ion in aqueous solutions. Sensors Actuators, B: Chemical. 203: 35–43 **(9 pages).**

Djamudin, D.; Fauzi, A.M.; Arifin, H.S.; Sukardi, S., (2012). Studi Pengembangan Agroindustri Dan Agrowisata Terpadu Di

Daerah Aliran Sungai (Das) Kali Bekasi Kabupaten Bogor. J. Teknologi Industri Pertanian. 22(3): 151–163 **(13 pages).**

Effendi, H., (2003). Telaah Kualitas Air Bagi Pengelolaan Sumber Daya dan Lingkungan Perairan. Yogyakarta: Kanisius.

Effendi, H.; Prayoga, G.; Azhar, A.R.; Permadi, T.; Santoso, E.N., (2021). Pollution index of Cileungsi-Cikeas-Bekasi river. IOP Conference Series: Earth Environ.Sci., 744(1): 1-7 **(7 pages).**

Giao, N.T.; Anh, P.K.; Nhien, H.T., (2021). Spatiotemporal analysis of surface water quality in Dong Thap Province, Vietnam Using Water Quality Index and Statistical Approaches. Water. 13(336): 1-19 **(19 pages).**

Husodo, T.; Ali, Y.; Mardiyah, S.R.; Shanida, S.S.; Abdoellah, O.S.; Wulandari, I., (2021). Perubahan lahan vegetasi berbasis citra satelit di DAS Citarum, Bandung, Jawa Barat. Majalah Geografi Indonesia. 35(1): 54–63 **(10 pages).**

Kadir, A.; Ahmed, Z.; Uddin, M.M.; Xie, Z.; Kumar, P., (2022). Integrated approach to quantify the impact of land use and land cover changes on water quality of Surma River, Sylhet, Bangladesh. Water. 14(7): 1-16 **(16 pages)**.

Karima, A.; Kaswanto, R.L., (2017). Land use cover changes and water quality of Cipunten Agung Watershed Banten. IOP Conference Series: Earth Environ.Sci., 54(1): 1-11 **(11 pages).**

Kaswanto, R.L.; Aurora, R.M.; Yusri, D.; Sjaf, S., (2021). Analisis Faktor Pendorong Perubahan Tutupan Lahan selama Satu Dekade di Kabupaten Labuhanbatu Utara. J. Ilmu Lingkungan. 19(1): 107–116 (**20 pages).**

Li, Y.; Ma, L.; Li, Y.; Abdyzhapar, S.; Abuduwaili, J., (2022). Exploration of the driving factors and distribution of fecal coliform in rivers under a traditional agro-pastoral economy in Kyrgyzstan, Central Asia. Chemosphere. 286: 1-9 **(9 pages).**

Namugize, J.N.; Jewitt, G.; Graham, M., (2018). Effects of land use and land cover changes on water quality in the Mngeni river catchment, South Africa. Phys. Chem. Earth. 1-40 **(40 pages).**

Nascimento, L.P.; Reis, D.A.; Roeser, H.M.; Santiago, A.D., (2019). Relationship between land use and water quality in a watershed impacted by iron ore tailings and domestic sewage. Rev. Ambient. Água., 14(5): 1-11 **(11 pages)**.

Nong, X.; Shao, D.; Xiao, Y.; Zhong, H., (2019). Spatio-Temporal Characterization Analysis and Water Quality Assessment of the South-to-North Water Diversion Project of China. Int. J. Environ. Res. Public Health. 16(2227): 1-23 **(23 pages)**.

Paná, S.; Marinelli, M.; Bonansea, M.; Ferral, A.; DonatellaValente; CamachoValdez, V., (2024). The multiscale nexus among land use-land cover changes and water quality in the Suquía River Basin, a semi-arid region ofArgentina. Sci. Rep., 14(4670): 1-14 **(14 pages)**.

Parmar, K.S.; Bhardwaj, R., (2014). Water quality management using statistical analysis and time-series prediction model. Appl Water Sci., 1:1-11 **(11 pages)**.

Pasisingi, N.; Pratiwi, N.; Krisanti, M., (2014). Kualitas perairan Sungai Cileungsi bagian hulu berdasarkan kondisi fisik-kimia. Depik. 3(1): 56-64 **(9 pages).**

Patricia, C.; Astono, W.; Hendrawan, D.I., (2018). Kandungan nitrat dan fosfat di Sungai Ciliwung. Seminar Nasional Cendekiawan. 4(4): 179–185 **(7 pages).**

Pratama, M.A.; Immanuel, Y.D.; Marthanty, D.R., (2020). A multivariate and spatiotemporal analysis of water quality in Code River, Indonesia. The Sci. World J., 2020:1-11 **(11 pages)**.

Putri, A.; Jana, R.; Florensia, A.S.; Asmara, A A.; Yulianto, A.; Brontowiyono, W., (2021). A Spatiotemporal Analysis of Water Quality and Land Use in Tambayakbayan River, Yogyakarta. IOP Conference Series: Earth Environ.Sci., 933(1): 1-10 **(10 pages).**

Rahman, M.W.; Purwanto, M.Y.; Suprihatin, S., (2014). Water Quality Status and Land Use Conservation Effort in the Upper Citarum Watershed, Bandung Regency. J. Nat. Resour. Environ. Manage., 4(1): 24–34 **(11 pages).**

Rajesh, M.; Rehana, S., (2022). Impact of climate change on river water temperature and dissolved oxygen: Indian riverine thermal regimes. Sci. Rep., 12(1): 1–12 **(12 pages).**

Rajwa-Kuligiewicz, A.; Bialik, R.J.; Rowiński, P.M., (2015). Dissolved oxygen and water temperature dynamics in lowland rivers over various timescales. J. Hydrol. Hydromech., 63(4): 353–363 **(11 pages).**

Ramadhawati, D.; Wahyono, H.D.; Santoso, A.D., (2021). Pemantauan Kualitas Air Sungai Cisadane Secara Online Dan Analisa Status Mutu Menggunakan Metode Storet. J. Sains Teknologi Lingkungan. 13(2): 76–91 **(16 pages).**

Riani, E.; Butet, N.A.; Ansori, M.; Cordova, M.R., (2024). Impact of heavy metal pollution on the use of fishing pond land, a former site of used battery smelting. Global J. Environ.Sci. Manage., 10(4): 1655–1674 **(20 pages).**

Rodríguez-Romero, A. J.; Rico-Sánchez, A. E.; Mendoza-Martínez, E.; Gómez-Ruiz, A.; Sedeño-Díaz, J. E.; López-López, E., (2018). Impact of changes of land use on water quality, from tropical forest to anthropogenic occupation: A multivariate approach. Water. 10(1518): 1-16 **(16 pages).**

Roy, B.N.; Roy, H.; Rahman, K.S.; Mahmud, F.; Bhuiyan, M.M.; Hasan, M., (2024). Principal component analysis incorporated water quality index modeling for Dhaka-based rivers. City Environ. Interact., 23(100150): 1-11 **(11 pages)**.

Sato, Y.; Ishihara, M.; Fukuda, K.; Nakamura, S.; Murakami, K.; Fujita, M., (2018). Behavior of nitrate-nitrogen and nitrite-nitrogen in drinking water. Biocontrol Sci., 23(3): 139–143 **(5 pages).**

Setyowati, R.D., (2016). Studi Literatur Pengaruh Penggunaan Lahan Terhadap Kualitas Air. J. Ilmu-Ilmu Teknik. 12(1): 7-15 **(9 pages).**

Siahaan, R.; Indrawan, A.; Soedharma, D.; Prasetyo, L.B., (2011). Kualitas Air Sungai Cisadane, Jawa Barat - Banten. J. Ilmiah Sains., 15(1): 268-273 **(6 pages).**

Soewandita, H.; Sudiana, N., (2018). Studi Dinamika Kualitas Air Das Ciliwung. J. Air Indones., 6(1): 24–33 **(10 pages).**

Suharyanto, A.; Maulana, A.; Suprayogo, D.; Devia, Y.P.; Kurniawan, S., (2023). Land surface temperature changes caused by land cover/ land use properties and their impact on rainfall characteristics. Global J. Environ Sci. Manage., 9(3): 353–372 **(20 pages).**

Supardi, S.; Hariyadi, S.; Fahrudin, A., (2017). Analisis Keberlanjutan Pembangunan Kota Tepian Pantai (Studi Kasus: Kota Baubau Provinsi Sulawesi Tenggara). J. Wilayah Dan Lingkungan. 5(3): 188-204 **(17 pages).**

Supriatin, L.S.; Cahyono, W.E.; Syafrizon, S., (2017). The Effect of Rainwater Quality on The Methane Concentration. J. Kimia Dan Pendidikan Kimia. 2(2): 103-109 **(7 pages).**

Sutrisno, A.J.; Kaswanto, R.L.; Arifin, H.S., (2018). Spatial and temporal distribution of nitrate concentration in Ciliwung River, Bogor City. IOP Conference Series: Earth Environ. Sci., 179(1): 1-7 **(7 pages).**

Syawal, M.S.; Wardiatno, Y.; Hariyadi, S., (2016). Pengaruh Aktivitas Antropogenik Terhadap Kualitas Air, Sedimen dan Moluska di Danau Maninjau, Sumatera Barat. J. Biologi Tropis. 16(1): 1–14 **(14 pages).**

Takarina, N.D.; Chuan, O.M.; Pin, T.G.; Femnisya, I.; Fathinah, A.; Ramadhan, A.N., (2023). Land use variation impacts on trace elements in the tissues and health risks of a commercial fish. Global J. Environ.Sci. Manage., 9(3): 445–462 **(18 pages).**

Thomas, E.O., (2023). Evaluation of groundwater quality using multivariate, parametric and non-parametric statistics, and GWQI in Ibadan, Nigeria. Water Sci., 37(1): 117-130 **(14 pages)**.

Umwali, E.D.; Kurban, A.; Isabwe, A.; Mind'je, R.; HosseinAzadi; ZengkunGuo, (2021). Spatio-seasonal variation of water quality infuenced by land use and land cover in Lake Muhazi. Sci. Rep., 11(17376): 1-16 **(16 pages)**.

Varol, M., (2020). Spatio-temporal changes in surface water quality and sediment phosphorus content of a large reservoir in Turkey. Environ. Pollut., 259(113860): 1-9 **(9 pages)**.

Wiriani, E.R.; Syarifuddin, H.; Jalius, J., (2018). Analisis Kualitas Air Sungai Batanghari Berkelanjutan Di Kota Jambi. J. Pembangunan Berkelanjutan. 1(82): 123-141 **(19 pages).**

Wulandari, N.; Perwira, I.Y.; Ernawati, N.M., (2021). Profil Kandungan Fosfat pada Air di Daerah Aliran Sungai (DAS) Tukad Ayung, Bali. Curr. Trends Aquatic Sci., 4(2): 108–115 **(18 pages).**

Yaakub, N.; Raoff, M.N.; Haris, M.N.; Halim, A.A.; Kamarudin, M.K., (2018). Water Quality Index Assesment Around Industrial Area In In Kuantan, Pahang. J. Fundam. Appl. Sci., 9(2S): 731-749 **(19 pages).**

Yang, W.; Zhao, Y.; Wang, D.; Wu, H.; Lin, A.; He, L., (2020). Using Principal Components Analysis and IDW Interpolation to Determine Spatial and Temporal Changes of Surface Water Quality of Xin'anjiang River in Huangshan, China. Int. J. Environ. Res. Public Health. 17(2942): 1-14 **(14 pages)**.

Zhang, X.; Zhang, Y.; Shi, P.; Bi, Z.; Shan, Z.; Ren, L., (2021). The deep challenge of nitrate pollution in river water of China. Sci. Total Environ., 770: 1-12 **(12 pages).**

Zhang, Z.; Li, J.; Hu, Z.; Zhang, W.; Ge, H.; Li, X., (2023). Impact of Land Use/Land Cover and Landscape Pattern on Water Quality in Dianchi Lake Basin, Southwest of China. Sustainability. 15(3145):1-20 **(20 pages)**.

Zhang; Xiaoyue; Zhi, X.; Chen, L.; Shen, Z., (2020). Spatiotemporal variability and key influencing factors of river fecal coliform within a typical complex watershed. Water Res., 178: 1-11 **(11 pages).**

AUTHOR (S) BIOSKETCHES

Marisi, D.P., Ph.D. Candidate, Junior Researcher, Doctoral Program in Natural Resources and Environmental Management Sciences (NREMS), IPB University, Bogor,16680,Indonesia.
- Email: *dany.poltak.marisi@apps.ipb.ac.id*
- ORCID: 0009-0003-6026-1851
- Web of Science ResearcherID: NA
- Scopus Author ID: 58705792900
- Homepage: https://ipb.ac.id

Suprihatin, Ph.D., Professor, Department of Agroindustrial Technology, Faculty of Agricultural Engineering and Technology, IPB University, Bogor, 16680, Indonesia.
- Email: suprihatin@apps.ipb.ac.id
- ORCID: 0000-0001-9641-8820
- Web of Science ResearcherID: GNH-5658-2002
- Scopus Author ID: 56085767200
- Homepage: https://tin.ipb.ac.id

Hariyadi, S., Ph.D., Associate Professor, Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Bogor, 16680, Indonesia.
- Email: *sigidh@apps.ipb.ac.id*
- ORCID: 0000-0001-5888-1945
- Web of Science ResearcherID: NA
- Scopus Author ID: 56826194600
- Homepage: https://ipb.ac.id

Kaswanto, R.L., Ph.D., Associate Professor, Department of Landscape Architecture, Faculty of Agriculture, IPB University, Bogor, 16680, Indonesia.
- Email: *kaswanto@apps.ipb.ac.id*
- ORCID: 0000-0001-6036-9799
- Web of Science ResearcherID: NA
- Scopus Author ID: 57193559707
- Homepage: https://ipb.ac.id

HOW TO CITE THIS ARTICLE

Marisi, D.P.; S. Suprihatin; Hariyadi, S.; Kaswanto, R.L., (2025). The impacts of land use and cover change on water quality of watershed basin. Global J. Environ. Sci. Manage., 11(2): 573-592.

DOI: 10.22034/gjesm.2025.02.12

URL: https://www.gjesm.net/article_719779.html

Global J. Environ. Sci. Manage. 11(2): 593-608, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Hydrodynamic simulation experiment of tidal pump in strait waters

W.S. Pranowo[1,2,3,*], K. Malik[1,4], D. Adrianto[1,4], A. Kurniawan[1,5]

[1] *Study Program of Oceanography, Indonesian Naval Postgraduate Military Service School (STTAL), West Kelapa Gading, Jakarta, Indonesia*

[2] *Research Center for Climate and Atmosphere (BRIN), B.J. Habibie Science and Technological Park, South Tangerang City, Banten, Indonesia*

[3] *Korea-Indonesia Marine Technology Cooperation and Research Center, Jakarta, Indonesia*

[4] *Hydro-Oceanography Center, Indonesian Navy, Jl. Pantai Kuta V/1, East Ancol, North Jakarta, Indonesia*

[5] *Faculty of Geography, Universitas Gadjah Mada, Jl. Kaliurang, Sekip Utara, Bulaksumur Sinduadi Sleman, Yogyakarta, Indonesia*

ARTICLE INFO

Article History:
Received 05 September 2024
Revised 09 December 2024
Accepted 13 January 2025

Keywords:
Bangka Strait
Downwelling
Numerical model
Tidal pump
Upwelling

ABSTRACT

BACKGROUND AND OBJECTIVES: Tidal phenomena, characterized by the rise and fall of sea surface levels, play a critical role in marine dynamics, including the formation of upwelling and downwelling currents. These currents significantly influence nutrient distribution and material exchange in coastal waters. The objective of this study is to analyze the vertical current movements generated by tidal pumping in the Bangka Strait, with a particular focus on their association with tidal asymmetry and changes in the underwater topography.

METHODS: A numerical simulation approach was employed using the Mike 3 Flexible Mesh software to model the hydrodynamics of the Bangka Strait. The input data included tidal measurements from the Geospatial Information Agency and bathymetric data from the Indonesian Navy Hydro-Oceanography Center. Over a duration of nine days, the simulation examined tidal patterns and their role in influencing vertical currents. Statistical methods were employed to validate the model, demonstrating a significant correlation and negligible errors when comparing simulation results and field data.

FINDINGS: The study revealed that during high tide, upward currents (upwelling) were observed with speeds ranging from 0.0005 to 0.0016 meters per second, while during low tide, downward currents (downwelling) occurred with speeds 0.0002 to 0.0035 meters per second. Significant alterations in vertical current direction were observed due to bathymetric changes, particularly within the depth range of 2 to 6 meters. There was a clear indication of tidal asymmetry, with the northern Bangka Strait exhibiting a tidal range of 3.8 meters, while the southern region recorded a range of 2 meters. These variations influenced vertical current speeds and nutrient distribution patterns. This study demonstrated that the K_1 amplitude exhibited the most pronounced increase during a supermoon event, pointing to a likely strong correlation.

CONCLUSION: The findings demonstrate the significant role of tidal pumping in shaping the hydrodynamics of the Bangka Strait, with implications for nutrient mixing and material transport. The outcomes yield significant information that can aid in the stewardship of coastal resources and the advancement of sustainable infrastructure in marine ecosystems. This study underscores the importance of numerical modeling in understanding complex marine dynamics and highlights the need for continued research to address the ecological and environmental impacts of tidal-induced currents.

DOI: 10.22034/gjesm.2025.02.13

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
63

NUMBER OF FIGURES
9

NUMBER OF TABLES
5

*Corresponding Author:
Email: *widodo.setiyo.pranowo@gmail.com*
Phone: +62821 1163 7144
ORCID: 0000-0002-5798-4181

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Bangka Strait is geographically a narrow gap between Bangka Island and the eastern mainland of South Sumatra. The strait holds significant economic importance for South Sumatra and Bangka Island, serving as a gateway to the maritime world for both regions (Zubir, 2015; Kurniawan *et al*., 2021), and contributing to the progress of maritime activities in western Indonesia. Since the Srivijaya period, the Bangka Strait has played a vital role as a key shipping channel. Previous studies indicate that this route has played a significant role in fostering human interaction and the dissemination of culture, owing to its advantageous geographical position (Fauziyah *et al*., 2022). In addition to trade and economic activities, the strait has been observed to play an important role in mining, with Bangka Island being the largest offshore tin mining site in Indonesia (Pamungkas and Husrin, 2020). Recognizing the vital role of the Bangka Strait, it is imperative to develop a thorough knowledge of its hydrodynamic features (Ambalika *et al*., 2019; Fauziyah *et al*., 2022; Kusumawardani *et al*., 2024). The objective of this study is to utilize numerical modeling techniques to simulate the hydrodynamic conditions of the Bangka Strait. The simulation results are anticipated to provide insights into the past, present, and future conditions of the waters. The insights gained from these observations can be instrumental for port and water engineering projects, ensuring that developments associated with the sea do not compromise existing biological resources. Various marine dynamics phenomena, such as upwelling and downwelling, are produced by vertical current movements from the bottom to the surface or vice versa (Nakanowatari *et al*., 2021; Cheng *et al*., 2022). These currents are typically caused by wind pushing sea surface layer (Johnston and Colin 2022; Podymov *et al*., 2023), creating a void in the water mass above it (Trautman and Walter, 2021). Based on observation, upwelling and downwelling can also occur due to seabed topography and changes in the physical properties of seawater, including temperature, salinity, and density in the water column (Coogan *et al*., 2019; Lorente *et al*., 2020; He and Mahadevan, 2021; Johnston and Colin, 2022; Leclercq *et al*., 2024; Li *et al*., 2024). Moreover, it has been established that these currents may be impacted by tidal pumps in certain conditions and specific locations. Tidal movements, characterized by the cyclical rise and fall of sea levels, are driven by the gravitational forces exerted by the moon and sun, as well as the seabed's topographical characteristics (Sarkar *et al*., 2019; Huang and Li, 2024; Li *et al*., 2024; Zou *et al*., 2024). During these movements, tidal pump (Xiao *et al*., 2018; Wu, 2021), stirs nutrients (Liu *et al*., 2017; Zhao *et al*., 2023; Li *et al*., 2024), temperature, and salinity in the water column (Becherer *et al*., 2016; Stevens and Smith, 2016; Zhao *et al*., 2019; Du *et al*., 2022; Xu *et al*., 2023). The process occurs continuously during tidal phenomena, specifically in estuarine areas (Becherer *et al*., 2016). In stratified coastal waters, surface and bottom tidal currents rotate in opposite directions, resulting in upwelling on one side and downwelling on the other, depending on the current's orientation (Xu *et al*., 2023). In relatively narrow straits, the localized effects of tidal pumping significantly influence the broader dynamics within the strait region (Xiao *et al*., 2018; Zhou *et al*., 2020; Martín *et al*., 2023). Straits serve as key connectors between seas or oceans, where tidal differences on either side can generate strong currents, driving water movement (Cucco *et al*., 2016). This mechanism enables the movement of materials across the strait, encompassing sediments, nutrients, and potentially harmful pollutants (Fourniotis, 2024). The tidal pumping process in straits typically occurs when tidal height differences on either side create a pressure gradient strong enough to drive water through the strait (Børve *et al*., 2021; Hosseini *et al*., 2023). In instances of tidal asymmetry, where high tide is experienced on one side of the strait while the opposite side experiences low tide, water flows from the high-tide area to the low-tide area, carrying with it suspended particulate matter. As the tidal cycle progresses and the gradient reverses, the resulting bidirectional flow facilitates the exchange of water masses, enhancing nutrient redistribution and contributing to the dispersal of pollutants across broader spatial scales (Yin *et al*., 2022; Fu *et al*., 2023; Xu *et al*., 2023). This phenomenon plays a vital role in marine ecosystems and has important consequences for coastal water quality and human activities, including fisheries and maritime transportation. The ecological impacts of tidal pumping in straits vary widely, depending on the physical characteristics of the strait—such as depth, width, and seafloor topography—as well as the prevailing tidal conditions (Jeon *et al*., 2024). Under

particular circumstances, tidal pumping may increase biological productivity by transferring nutrients from the deep ocean to shallower coastal regions, which in turn supports the proliferation of phytoplankton and other marine organisms (Zhao *et al.*, 2019). However, in other straits, this phenomenon can contribute to the distribution of pollutants or hazardous materials, potentially harming local ecosystems and posing risks to human health (Zhao *et al*., 2019). In areas near significant urban centers or industrial zones, tidal pumping can facilitate the movement of pollutants from sources of contamination to wider regions, thereby affecting water quality and marine ecosystems (Hananto and Prananda, 2020). Recent research on tidal pumping highlights the complexity of this phenomenon and underscores the importance of a deeper understanding for effective coastal resource management. Zhao *et al*. (2023) exploring the use of tidal pumping as a mechanism for alternative energy inputs, presenting promising opportunities for sustainable energy advancement and the optimization of coastal resources. Kersten *et al*. (2022) and Liu *et al*. (2017) state that tidal pumping is recognized as a primary driving force influencing water exchange between land and sea, biogeochemical reactions within tidal aquifers, and nutrient loading to the ocean. Understanding tidal pumping in straits is vital, especially considering the impacts of climate change, which can disrupt global tidal patterns and subsequently affect the mechanisms of tidal pumping. Sea-level rise and climate change may reshape the physical characteristics of straits, such as their width and depth, potentially modifying the intensity and impacts of tidal pumping. Consequently, additional research is essential to forecast the future development of this phenomenon and to determine how coastal resource management can be modified to respond to these changes. Overall, tidal pumping in straits is a complex and dynamic process with significant implications for marine ecosystems and human activities in coastal areas. Recent studies have provided valuable insights into its mechanisms and impacts, but much remains to be learned to ensure that coastal management can accommodate ongoing environmental changes. To protect sensitive ecosystems and promote the sustainable use of marine resources in the future, it is vital to adopt a more integrative and science-driven approach to the management of straits and coastal areas. Given the strategic position of the Bangka Strait as a transportation corridor and an ecological migration route. This study aims to examine and analyze the occurrence of upwelling and downwelling phenomena induced by tidal pump in Bangka Strait in Indonesia using the Mike 3 FM numerical modeling software in 2022. The data used include depth, and water level condition along boundary of Bangka Strait of Indonesia.

MATERIALS AND METHODS

The input used for the boundary model area comprised tidal data from the geospatial information agency or badan informasi geospasial (BIG), with measurements from Muntok Station in the north at 2° 5’ 5.64” south (S) - 105° 7’ 58.8” east (E) and Sadai Station in the south at 3° 0’ 51.48” S - 106° 26’ 49.2” E). The model simulation lasted for 1 hour (h) each day from July 18 to July 26, 2022. This date range was selected as it corresponds with the supermoon event that peaks during the eastern season in July 2022. It is also important to state that bathymetry data comprised digitization from nautical chart number 104 of the Indonesian Navy Hydro-Oceanography Center (Pushidrosal), which had a scale of 1:500.000. The analysis excludes various external influences, such as wind and the contribution of freshwater from river mouths, concentrating instead on the principles of barotropic modeling as outlined by (Ding *et al*., 2012; Nugroho *et al*., 2018; Ajiwibowo and Pratama, 2022). Fig. 1 presents a graphical representation of the research flowchart.

The present study included the use of a quantitative method with mathematical equations and the proposed model was validated using statistical analysis, which comprised tables, graphs, images, and diagrams. The configuration of the model design employed during the exploration is detailed in Table 1.

The model domain utilizes a flexible mesh, with the mesh formation criteria detailed in Table 2. Following this, depth interpolation was conducted utilizing the digitized Indonesian Nautical chart, employing the Natural Neighbor method.

Throughout this research, the simulation outcomes were analyzed both horizontally and vertically to assess the existing conditions within the water column. The three-dimensional model simulation divided the current into three components,

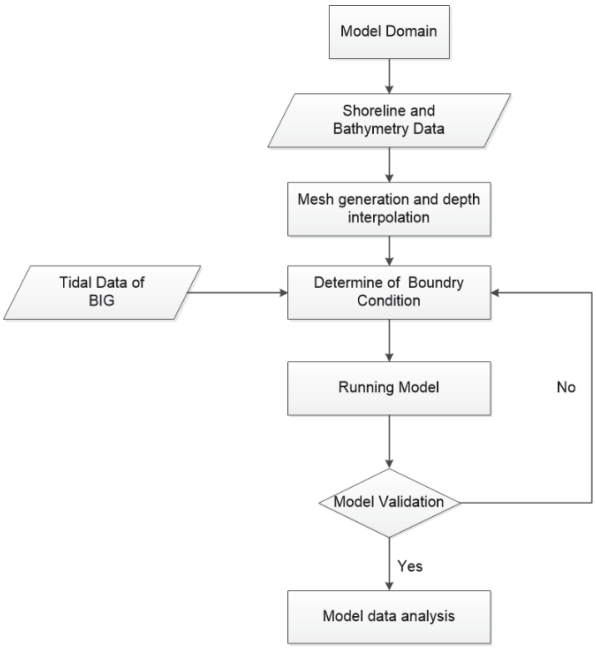


Fig. 1: The study flowchart

Table 1: Model design configuration

Parameter	Description
Simulation period	18/07/2022 – 26/07/2022
Time interval	3600 second
Number of time intervals	192
Horizontal eddy viscosity	Smagorinsky formulation
Vertikal eddy viscosity	Log law formulation
Bed resistance	Roughness height

Table 2: Mesh formation criteria in the model area

No.	Mesh	Description
1	Maximum elements	$2x10^{-3}$ deg^2. ($degree^2$)
2	Smallest angle	26°
3	Number of elements	14751
4	Number of points	7959

namely u and v representing horizontal currents as well as w representing vertical currents. In line with prior studies, a positive vertical velocity (w) suggests that the current is moving upward, a phenomenon termed upwelling. In contrast, a negative vertical velocity indicates a downward current, commonly referred to as downwelling (Mustikasari *et al*., 2015). Accordingly, the developed model overlaid the surface hydrodynamic phenomenon with w velocity value to examine the upwelling or downwelling phenomena in Bangka Strait. The design of the vertical cross-section was executed along the Bangka Strait, as indicated by the coordinates detailed in Table 3.

Study location including mesh formation, depth interpolation results, tidal station positions as validation of the model results, are shown in Fig. 2. The model was developed using the three-dimensional incompressible Reynolds average Navier

Table 3: Vertical profile coordinate of Bangka Strait

Point	Longitude	Latitude
1	104.9602	-2.01337
2	105.3421	-2.27635
3	105.6834	-2.32331
4	105.9025	-2.8524
5	106.2031	-3.00894

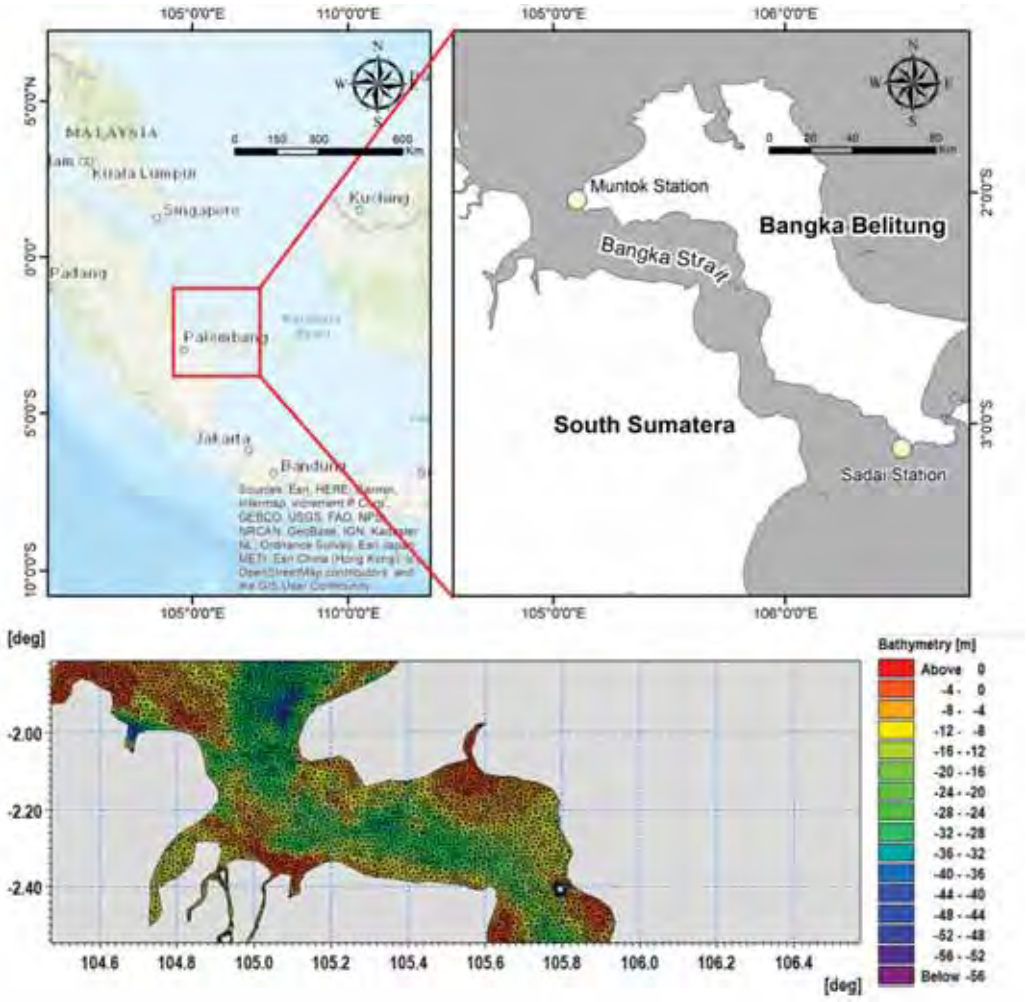


Fig. 2: Geographic location of the study araea in Bangka Strait of Indonesia, along with the mesh formation, depth interpolation results, validation tidal station positions

Stoke equation with the assumption of Boussinesq and hydrostatic pressure (Yasra *et al*., 2022). A three-dimensional numerical strategy was employed for the preparation, integrating the sigma and Z-level systems to maintain velocity at the water's bottom. Within the realm of oceanography, the sigma system serves as a discretization framework used in deep waters, facilitating the conversion of depth changes into the bottom layer by "stretching" vertical domain (Zamani and Koch, 2020). Furthermore, to obtain higher geometric resolution along the complex coastline, the unstructured grid was applied

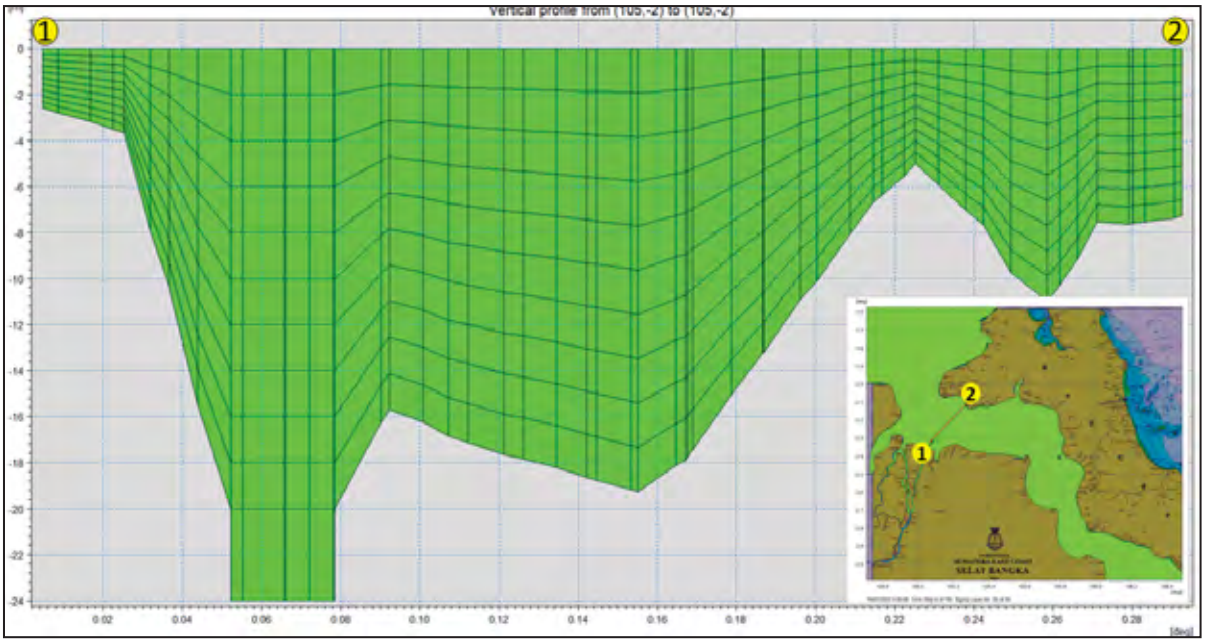


Fig. 3: Vertical cross-section of the combined sigma and Z-level methods (hybrid)

horizontally. This enabled the entire research area to be approached in accordance with actual conditions. This study implemented a vertical mesh that combined the sigma and Z-level coordinate systems, organized according to an equidistant framework. It is also important to state that the surface, to a depth of 20 meters (m) used the sigma method, while the rest utilized Z-level method with a grid spacing of 4 m as shown in Fig. 3. The formulation of Continuity in Cartesian plane can be used as Eq. 1 (DHI 2017):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Meanwhile, the momentum equations on the x, y, and z axes can be shown as Eqs. 2, 3 and 4 (DHI, 2017):

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}= fv-\frac{1}{\rho_0}\frac{\partial q}{\partial x}-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}- \frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial x}+F_u-F_{vx}+\frac{\partial}{\partial z}\left(v_t^v\frac{\partial u}{\partial z}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}+\frac{\partial wv}{\partial z}= -fu-\frac{1}{\rho_0}\frac{\partial q}{\partial y}-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}- \frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial y}+F_v-F_{vy}+\frac{\partial}{\partial z}\left(v_t^v\frac{\partial v}{\partial z}\right) \tag{3}$$

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial vw}{\partial y}+\frac{\partial w^2}{\partial z}= -\frac{1}{\rho_0}\frac{\partial q}{\partial z}+F_w-F_{vz}+\frac{\partial}{\partial z}\left(v_t^v\frac{\partial w}{\partial z}\right) \tag{4}$$

Where, t is time, x, y, and z are Cartesian coordinates, η represents surface elevation, u is the x-axis velocity component, v denotes the y-axis velocity component, w is the z-axis velocity component, and f is Coriolis parameter with $f=2\Omega\sin\phi$ (Ω is the angle of revolution and ϕ is the geographic latitude). Furthermore, other parameters of the equation include v_t^v, which represents vertical eddy viscosity, g, the acceleration due to gravity, p_a atmospheric pressure on the surface, ρ water density, ρ_0 reference density and F, horizontal

diffusion. The sigma method on vertical plane of the S coordinate discretization was in accordance with formation by Song and Haidvogel (1994), where the first vertical equidistant discretization (-1≤ s ≤ 0) was applied, using Eq. 5 (Song and Haidvogel, 1994):

$$S_i = -\frac{N_\sigma + 1 - i}{N_\sigma} \quad \text{with } i = 1,(N_\sigma + 1) \tag{5}$$

The sigma coordinate system formulation is discretized, using Eqs. 6 and 7 (Song and Haidvogel, 1994):

$$\sigma_i = 1 + \sigma_c S_i + (1 - \sigma_c) C(S_i) \text{ with } i = 1,(N_\sigma + 1) \tag{6}$$

Where :

$$C(S) = (1-b)\frac{\sin(\Theta_s)}{\sin(\Theta)} + b\frac{\tanh\left(\Theta\left(s+\frac{1}{2}\right)\right) - \tanh\left(\frac{\Theta}{2}\right)}{2\tanh\left(\frac{\Theta}{2}\right)} \tag{7}$$

Where; σc is a weighting factor between the equidistant distribution and the strain formulation (0 < σc ≤ 1), with 1 showing an equidistant distribution and 0 showing a strain distribution. Furthermore, Θ is the surface control parameter (0 < θ ≤ 20), and b represents the basic control parameter (0 ≤ b ≤ 1).

Model validation

Following the successful execution of a model simulation, validation was carried out to evaluate the discrepancies between the model outcomes and the field data. Model validation incorporated several statistical formulations, all of which were used to evaluate the model results. The main statistical metric employed is the root mean square error (RMSE). This measure is commonly utilized to assess the precision of predictive data. In general, a prediction is considered close to accurate when RMSE value approaches zero, with a maximum tolerated limit of 0.4 for the model to be accepted. This formulation is widely regarded as an excellent tool for determining the level of error in modeling. RMSE value was calculated using Eq. 8 (Neill and Hashemi 2018):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2} \tag{8}$$

Once RMSE was determined, the Pearson correlation coefficient was utilized to analyze the relationship between the model results and the field data, allowing for an assessment of the correlation's strength (Smith, 2021). Generally, Pearson correlation is calculated using Eq. 9 (Smith, 2021):

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{\left(n\sum x^2 - (\sum x)^2\right)\left(n\sum y^2 - (\sum y)^2\right)}} \tag{9}$$

Table 4 presents the obtained results on the correlation between coefficients and relationship levels in the Pearson correlation method (Malik *et al*. 2023).

RESULTS AND DISCUSSION

Validation results

Results from the simulation demonstrate that the validation of surface elevation at the Muntok Station, in comparison to field data, achieved RMSE and correlation values of 0.17 and 0.98 respectively. The overlay between the model results graph and field data is shown in Fig. 4.

The validation results of the model's surface elevation at Sadai Station position with field data showed an RMSE value of 0.04 with a correlation value of 0.99. The overlay graph presented in Fig. 5 depicts the relationship between the surface elevation of the simulation results and the corresponding field data.

The validation results from both tidal observation stations show that the model performed well, as shown by the very small RMSE values below 0.4 and correlation values above 0.80, which reflects a strong correlation between the simulation results and field

Table 4: Pearson correlation table

Coefficient interval	Relationship level
0.00 – 0.199	Very low
0.20 – 0.399	Low
0.40 – 0.599	Moderate
0.60 – 0.799	Strong
0.80 – 1.000	Very strong

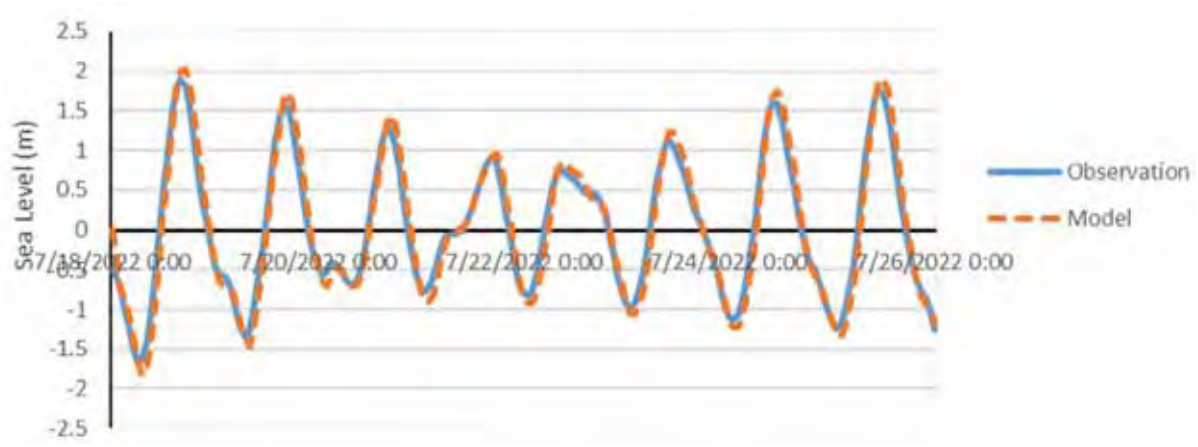


Fig. 4: Graph of field and model tidal validation at Muntok Station

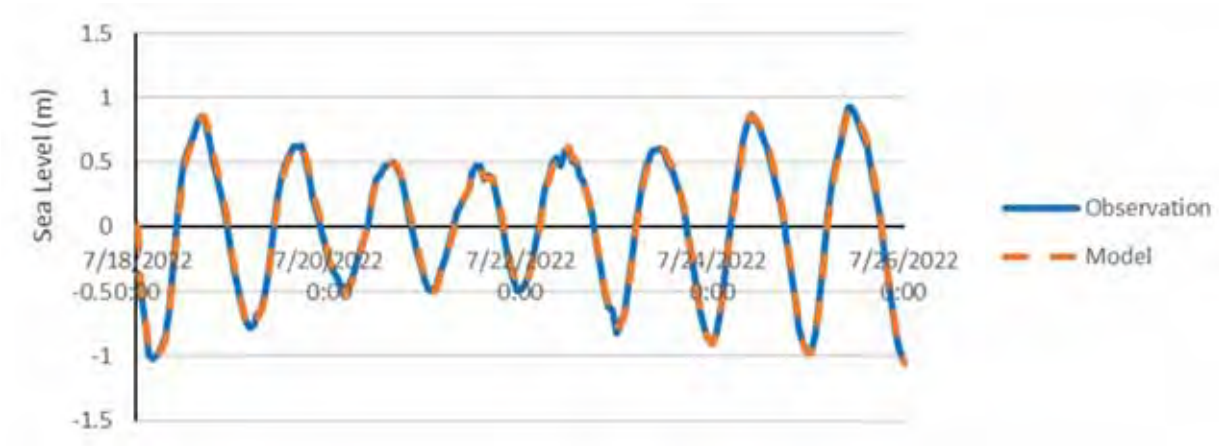


Fig. 5: Graph of field and model tidal validation at Sadai Station

data. The observations led to the conclusion that the results from the model simulation were appropriate for subsequent analysis. Surface elevation data from the model results at the two tidal stations, Muntok and Sadai, were used to perform harmonic component calculations adopting Within the Mike software, the Tide Analysis of Height tool is grounded in the least squares principle for its calculations. The tidal harmonic constants at Muntok and Sadai Stations are shown in Tables 5 and 6 respectively**.** Findings from the tidal harmonic constants at both stations reveal that K1 was the most prominent among the various constants. Qualitatively, this is in line with Hatayama *et al.* (1996) who stated that tidal propagation in the western Indonesian waters showed the K1 component to be more dominant than M2 component. The prevailing influence was linked to the tidal propagation emanating from the Pacific Ocean. Vertically, the movement of surface elevation along Bangka Strait, according to the vertical profile coordinate listed in Table 3 , shows that when approaching high tide, the surface elevation moves from the north and south of the strait towards the middle. As low tide approaches, the water begins to flow from the center of the strait, subsequently moving back toward both the northern and southern ends, as illustrated in Fig. 6.

The obtained results are also in line with Hatayama *et al.* (1996), where tidal propagation was described based on the constant K1 in Indonesian waters in Bangka Strait. This area serves as a junction for tidal flows originating from the Malacca Strait and the

Table 5: Tidal harmonic constants from the model results

No.	Muntok station			Sadai station	
	Name	Amp (m)	Phase (deg.)	Amp (m)	Phase (deg.)
1	Z0	0.0325	0	0.0096	0
2	K1	0.9166	61.48	0.5676	44.54
3	M2	0.3506	11.85	0.0751	293.44
4	M3	0.0244	313.29	0.0048	247.86
5	M4	0.0222	32.25	0.0105	92.14
6	2MK5	0.0198	40.69	0.0199	53.15
7	2SK5	0.0073	215.06	0.0006	337.9
8	M6	0.0051	358.19	0.0057	51.64
9	3MK7	0.0083	247.3	0.0043	209.82
10	M8	0.0118	349.66	0.0061	322.88

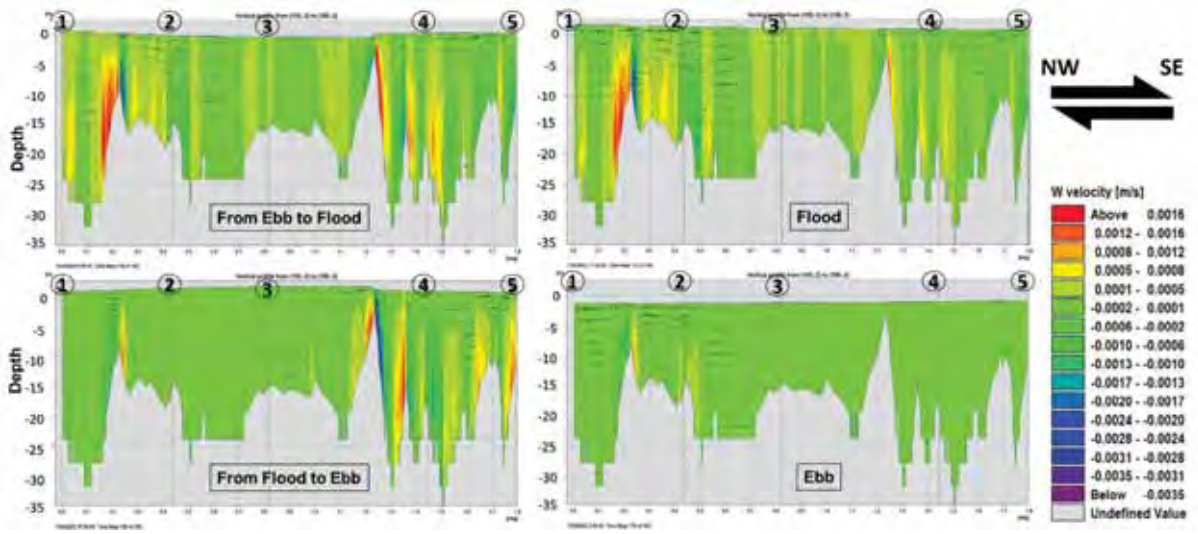


Fig 6: The surface elevation pattern movement along Bangka Strait based on Table 3 coordinate

South China Sea to the north, as well as the Java Sea in the south. Tidal propagation scheme in Indonesian waters is shown in Fig. 7.

Surface current circulation and vertical current

The surface current derived from the model simulation results exhibits a pattern consistent with the propagation of high water. As high tide approaches, the current is noted to flow into the strait's mouth from both the northern and eastern directions, converging at the center. Meanwhile, when approaching low tide, the current moved from the middle of the strait to the north and south, as shown in Fig. 8a and b. Fig. 8a and b show the color gradation represents w velocity component, with positive and negative w velocity values showing upwelling and downwelling respectively. Fig. 8, when viewed horizontally, shows that as high tide was approached, the area in the north of the strait with a w velocity above 0.00016 meter per second (m/s) became greater compared to the south. This condition indicates that the northern region of the strait underwent a significant upwelling phenomenon. Meanwhile, as low tide approaches, w velocity values in both the north and south tend to be homogeneous, around -0.00004 m/s, showiing downwelling currents.

Findings from the horizontal simulation reveal that with the approach of high tide, the W velocity value in the northern part of the strait is higher than that in the southern part (Fig. 8). This difference in W velocity was probably due to the varying water levels between the north and south of the strait. Tidal range

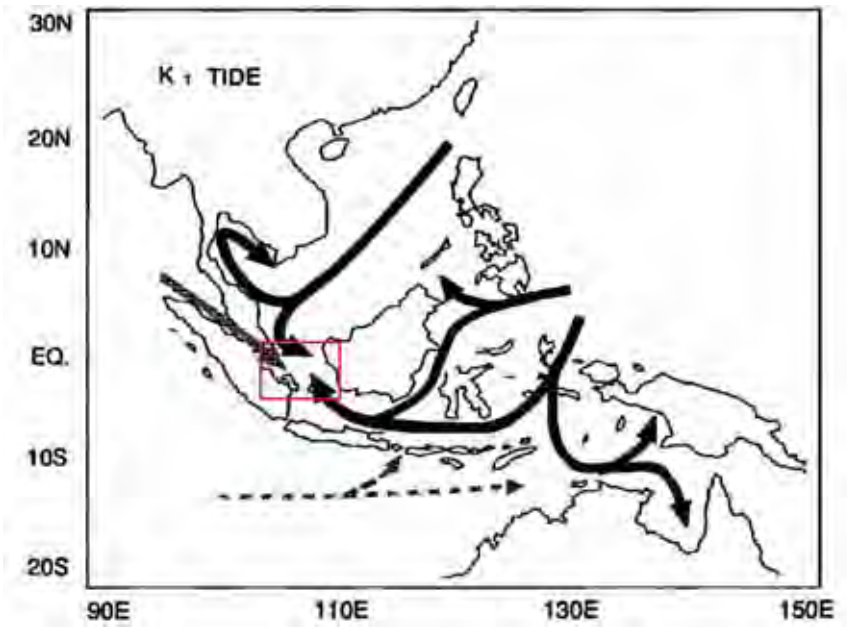


Fig 7: Tidal propagation scheme due to constant K1 in Indonesian waters, and red box is domain of the study (Hatayama *et al.,* 1996)

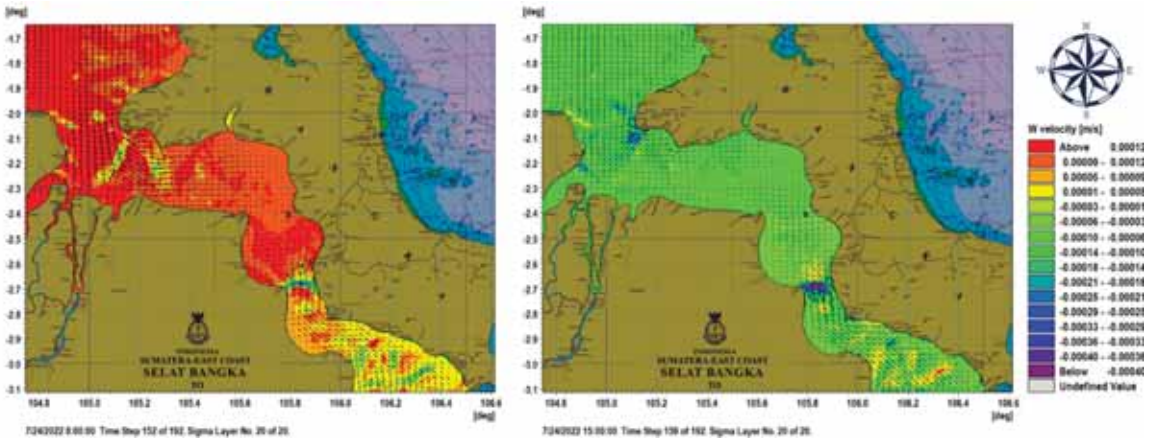


Fig. 8: Surface current pattern when approaching high tide (8a) and Surface current pattern when approaching low tide (8b)

in the north was approximately 3.8 m, while that of the south was only 2 m, as shown in Fig. 9.

The results obtained from the model simulation were analyzed vertically by cutting Bangka Strait following the coordinates and the scheme shown in Fig. 2, with the conditions presented in Fig. 6. As high tide was approached, the surface elevation at points 1, 2, and 3, points 4 and 5 of Bangka Strait was already at high tide. The vector W, extending from point 1 to point 2, demonstrated upwelling, but at depths of 6 and 2 m, it deflected downward. The current vector w between points 2 and 3 showed similar upward movement, which also deflected at depths of 6 and 2 m. With the arrival of low tide in the northern region (point 1) and southern areas (points 4 and 5) of the Bangka Strait, the surface elevation had dropped to low tide. In contrast, points 2 and 3 continued to experience high tide conditions. The current vector

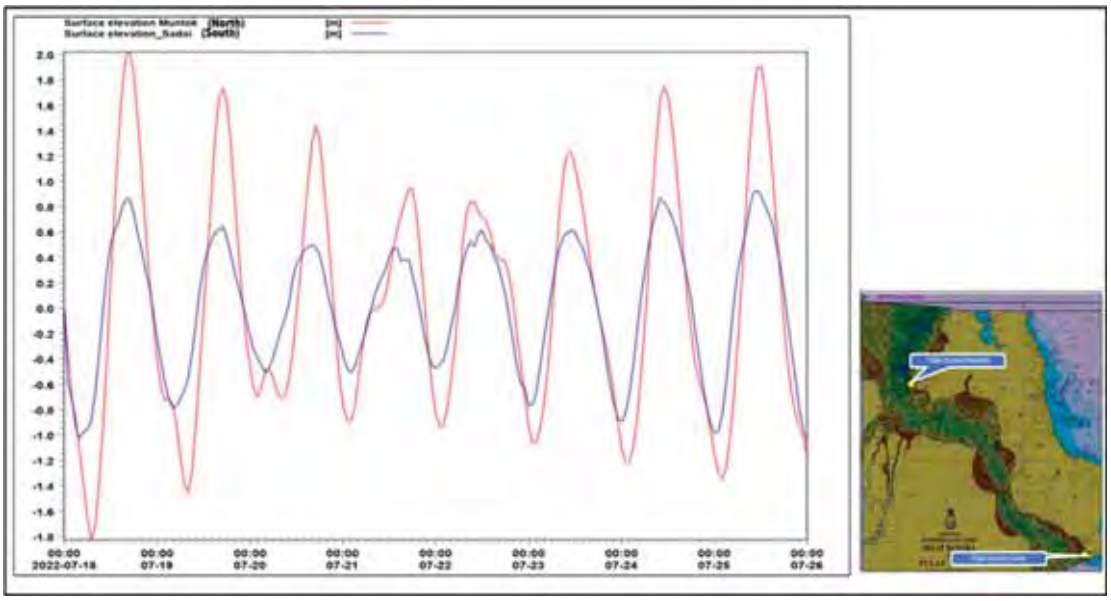


Fig. 9: The difference in tidal elevation between north and south stations

W from points 1 to 2 showed downwelling, with upward deflection at depths of 6 and 2 m. Between points 2 and 3, the current vector w also showed downwelling, which subsequently experienced upwelling deflection at the same depths. Overall, the findings from the model simulation demonstrated that the W component vector's movement in the water column conformed to a tidal pattern, observed in both horizontal and vertical dimensions. This was evidenced by the fact that as high tide was approached, w component vector moved upward, but as low tide was approached, it moved downward. Furthermore, the simulation revealed that variations in underwater topography affected the dynamics of upwelling and downwelling, aligning with the research conducted by. Sabhan *et al.* (2020). Topographic variations (e.g. sills) make a significant contribution to the formation of upward vertical currents (pumping/upward velocity), especially in the near-surface area seen in Fig. 6, and the results of this study are similar to those presented by Pranowo *et al.* (2014) and Nugroho *et al.*, (2018). Upwelling speed obtained from the simulation in Bangka Strait was observed to be between the range from 0.0005 to 0.0016 m/s, while downwelling speed ranged from 0.0002 to 0.0035 m/s presented in Fig. 6. These values were smaller than those reported by Pranowo *et al.* (2014) who examined Bone Bay waters in August 2004. During the investigation, Pranowo *et al.* (2014) stated that the upwelling speed value in Bone Bay area ranged from 0.0005 - 0.0035 m/s, while downwelling speed was between the range from 0.0005 - 0.0046 m/s. In similar aquatic environments, particularly the Ombai Strait, the documented vertical current velocity values appear to be marginally greater, attaining a maximum of 0.00076 m/s (Kurniawan *et al.*, 2023). Most tidal pump and upwelling experiments are currently conducted in estuarine areas or nearshore waters (Yu *et al.*, 2014; Ajiwibowo and Pratama, 2022; Du *et al.*, 2022; Zhao *et al.*, 2023) or laboratory-based experiments (Xiao *et al.*, 2018; Rahuna *et al.*, 2023). Only a small number of experiments have ever been recorded in the waters of the strait (Sánchez-Garrido *et al.*, 2015; Gonzalez *et al.*, 2023), and the main focus of several vertical current velocity experiments is the development of renewable energy (Calero *et al.*, 2014; Orhan and Mayerle, 2020; Hazim *et al.*, 2021; Ajiwibowo and Pratama, 2022). It is crucial to highlight that, apart from the differences in research sites between the strait and the bay, the discrepancies in results may also stem from the varying depths present in both areas. The Bangka Strait was found to have a depth of approximately ~30 m, in contrast to Bone Bay, which reached around 400 meters.

Nevertheless, research by Mustikasari *et al.* (2015), which simulated currents across all Indonesian waters over a one-year period, indicated that the upwelling speed during the East season (August) in Bangka Strait ranged of $5x10^{-6}$ – $2x10^{-5}$ m/s. It appears that this study produces higher upwelling speed, which is thought to be related to the different resolutions of the applied models. In general, this study uses a more detailed unstructured grid with more specific locations, so that the bottom topography of the waters can be better replicated. Hatayama *et al.* (1996) indicate that the tidal behavior in the Bangka Strait is shaped by interactions from surrounding regions, with the K_1 tide mainly resulting from tidal forces that come from the Pacific, in contrast to the M_2 tide, which is affected by inputs from both the Pacific and Indian Oceans. This regional variability underscores the role of tidal forcing from the Malacca Strait, South China Sea, and Java Sea in determining tidal stability and predictability. Under changing climate conditions, shifts in ocean circulation and sea-level rise could alter the dominance of Pacific or Indian-origin tidal forces, impacting the long-term behavior of tidal currents in the Bangka Strait. Comprehending these regional factors is important for predicting future tidal dynamics in this area. The study demonstrated that during a supermoon event, the K_1 amplitude had the most considerable increase, suggesting a robust potential correlation. This contrasts with the findings of Tiatama *et al*. (2024) in the waters of Semarang Bay (northern coast of Java), which stated that the 2022 supermoon phenomenon does not directly influence K_1 tidal components. In certain cases, K_1 refers to a tidal constant used in sea-level calculations, which is influenced by the gravitational forces of the Moon and the Sun on Earth. The tidal pumping phenomena observed in this study have potential long-term ecological and environmental implications in strait ecosystems for futher research. By improving the vertical mixing of water bodies, tidal pumping aids in the transfer of nutrients from the benthic zone to the photic zone, which in turn supports primary productivity and encourages biodiversity. However, it also poses potential risks, such as increased turbidity that may hinder photosynthesis, and the redistribution of pollutants like heavy metals and microplastics, which can disrupt food webs and ecosystem dynamics. Additionally, tidal pumping influences oxygen levels in the water column, potentially leading to hypoxic conditions in poorly ventilated areas. These diverse effects emphasize the importance of conducting further studies to measure the long-term implications and shape conservation strategies, particularly in light of shifting environmental circumstances and escalating anthropogenic pressures.

CONCLUSION

This study successfully validated the hydrodynamic simulation model for the Bangka Strait using tidal data from Muntok and Sadai Stations. The model recorded root mean square error values of 0.17 and 0.04, and correlation coefficients of 0.98 and 0.99, which signify a robust alignment with field data. These validation results confirm the robustness and reliability of the simulation in capturing the tidal dynamics of the Bangka Strait. The findings demonstrated that tidal pumping within the Bangka Strait is heavily influenced by the asymmetry of tides and changes in bathymetric variations. Tidal range differences, with 3.8 meters in the north and 2 meters in the south, created distinct patterns in vertical current dynamics. Upwelling was dominant during high tide, with velocities ranging from 0.0005 to 0.0016 meters per second, particularly in the northern region of the strait. In contrast, downwelling took place during low tide, exhibiting velocities ranging from 0.0002 to 0.0035 meters per second. Bathymetric topography significantly influenced vertical currents, particularly at depths between 2 and 6 meters, where changes in seabed slope caused deflections in current direction. Surface elevation patterns demonstrated a bidirectional flow, showing that water converges at the midpoint of the strait during high tide and spreads out to the north and south during low tide. The dominance of the K1 tidal harmonic constant in the Bangka Strait aligns with previous research on tidal propagation in Indonesian waters. The findings of this study indicated that the K_1 amplitude showed a significant increase during a supermoon event, suggesting a probable strong correlation. This highlights the significant contribution of tidal forces from the Pacific Ocean and the confluence of tidal movements from the Malacca Strait, South China Sea, and Java Sea. These interactions play a critical role in shaping the hydrodynamic characteristics of the Bangka Strait. In conclusion, this study provides valuable insights into the hydrodynamics of the Bangka Strait,

emphasizing the role of tidal pumping in influencing vertical currents and water column mixing. These results carry important practical consequences for the management of coastal resources, maritime navigation practices, and the preservation of ecosystems. Further research is recommended to explore seasonal variations, sediment transport, and the broader ecological impacts of tidal dynamics in this region.

AUTHOR CONTRIBUTIONS

W.S. Pranowo, the corresponding author, has main contributor with conceptualization, methodology, software, interpreted the results, formal analysis, data curation, writing - original draft preparation, visualization. K. Malik has contribute to data curation, methodology, software, formal analysis, writing - original draft preparation, visualization. D. Adrianto has contribute to investigation, resources, supervision, writing - review and editing. A. Kurniawan has contribute to visualization, validation, formal analysis, dan software.

ACKNOWLEDGEMENT

Tide data were obtained from BIG. Bathymetry data were obtained from Hydro-Oceanography Center (Pushidrosal). Modeling was conducted at the Hydro-Oceanography Laboratory, Indonesian Naval Postgraduate School (STTAL) in North Jakarta. Part of the analysis was conducted at the Climate and Atmospheric Research Center, National Research and Innovation Agency (BRIN).

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

°	Degree
′	Minue
″	Second
BIG	Badan informasi geospasial
Deg.	Degree
E	East
F	horizontal diffusion
f	Coriolis parameter
h	Hour
M	Model result data
m	Meters
m/s	meter per second
n	Number of data pairs X and Y
O	Field data (BIG data)
RMSE	Root mean square error
S	South
t	time
u	x-axis velocity component
v	y-axis velocity component
W	vertical velocity

η	surface elevation
g	acceleration due to gravity
Ω	angle of revolution
p_a	atmospheric pressure
ϕ	geographic latitude
ρ	water density
ρ_0	reference density
ν_t^v	vertical eddy viscosity
Σx	Total number of variables X
Σy	Total number of variables Y
Σx^2	Square of total number of variables X
Σy^2	Square of total number of variables Y
Σxy	Multiplication result of total number of variables X and Y

REFERENCES

Ajiwibowo; H.; Pratama, M. B., (2022). Hydrodynamic model and tidal current energy potential in Lepar Strait, Indonesia. Int. J. Renew. Energy Dev., 11(1): 15–25 **(11 pages)**.

Ambalika, I.; Irma, A.; Aditya, P.; Mohammad, N.; Umroh, (2019). Oceanography database development in Bangka Seas. Adv. Eng. Res., 167: 22-26 **(5 pages).**

Becherer; Johannes; Götz, F.; Lars, U.; Hans, B., (2016). Estuarine circulation versus tidal pumping: Sediment Transport in a well-mixed tidal inlet. J. Geophys. Res. Ocean., 121(8): 6251–6270 **(20 pages).**

Børve, E.; Päl, E.I.; Ole, A.N., (2021). Rectified tidal transport in lofoten-vesterälen, Northern Norway. Ocean Sci., 17(6): 1753–1773 **(21 pages).**

Calero Quesada; M. C.; García Lafuente, J.; Sánchez Garrido, J. C.; Sammartino, S.; Delgado, J., (2014). Energy of marine currents in the Strait of Gibraltar and its potential as a renewable energy resource. Renew. Sustain. Energy Rev., 34: 98–109 (12 pages).

Carballo, J.; Land, L.S.; Miser, D.E., (1987). Holocene dolomitization of supratidal sediments by active tidal pumping, sugarloaf key, Florida. J. Sediment. Res., 57(1): 153–165 **(13 pages).**

Cheng, C.; Zhaomin, W.; Luyu, S.; Chengyan, L., (2022). Modeling the thermal processes within the ice shelf–ocean boundary current underlain by strong pycnocline underneath a cold-water ice shelf using a 2.5-dimensional vertical slice model. Ocean Modelling. 177: 102079 **(19 pages).**

Coogan; J.; Dzwonkowski; B.; Lehrter; J., (2019). Effects of coastal upwelling and downwelling on hydrographic variability and dissolved oxygen in mobile Bay. J. Geophys. Res. Ocean., 124(2):791–806 **(16 pages).**

Cucco, A.; Giovanni, Q.; Antonio, O.; Leopoldo, F.; Alberto, R.; Matteo, S.; Costanza, T.; Roberto S., (2016). Hydrodynamic modelling of coastal seas: the role of tidal dynamics in the Messina Strait, Western Mediterranean Sea. Nat. Hazards Earth Syst. Sci., 16(7): 1553–1569 **(17 pages).**

DHI, (2017). MIKE 21 Dan MIKE 3 flow model FM. 1–64 **(64 pages).**

Ding; Y.; Bao, X.; Yu, H.; Kuang, L., (2012). A numerical study of the barotropic tides and tidal energy distribution in the Indonesian seas with the assimilated finite volume coastal ocean model. Ocean Dyn., 62(4): 515–532 **(18 pages).**

Du, Z.; Yu Q.; Peng, Y.; Wang, L.; Lin, H.; Wang, Y., Gao, S., (2022). The formation of coastal turbidity maximum by tidal pumping in well-mixed inner shelves. J. Geophys. Res. Ocean., 127(4): 1-29 **(29 pages).**

Fauziyah, A.; Setiawan, A.; Agustriani, F.; Rozirwan; Melki; Ningsih, E.N.; Ulqodry, T.Z., (2022). Distribution pattern of potential fishing zones in the Bangka Strait waters: An application of the remote sensing technique. Egypt. J. Remote Sens. Space Sci., 25(1): 257–265 **(9 pages).**

Fourniotis, N.T., (2024). Effect of internal waves on the hydrodynamics of a Mediterranean Sea strait. J. Mar. Sci. Eng., 12(4): 1–19 **(19 pages).**

Fu, M.; Lin, J.; Zhang, P.; Luo, W.; Zhang, J., (2023). Tide drives nutrients variation and exchange flux in the semi-enclosed Shuidong Bay coastal water in winter, South China Sea. Ocean Coast. Manage., 242: 106710 **(15 pages).**

Gonzalez; N. M.; Waldman, R.; Sannino, G.; Giordani, H.; Somot, S., (2023). Understanding tidal mixing at the Strait of Gibraltar: A high-resolution model approach. Prog. Oceanogr., 212: 102980 **(15 pages)**.

Hananto, P.W.H.; Prananda, R.R., (2020). Success story to eradicate the marine pollution in international strait or strait for international trade. Crepido, 2(2): 97–110 **(14 pages).**

Hatayama, T.; Awaji, T.; Akitomo, K., (1996). Tidal currents in the Indonesian seas and their effect on transport and mixing. J. Geophys. Res., 101: 12353-12373 **(21 pages).**

Hazim; S.; Salih, A.; Taha Janan, M.; Ouatouati, A. El; Ghennioui, A., (2021). Marine current energy assessment and the hydrodynamic design of the hydrokinetic turbine for the Moroccan Mediterranean Coast. Energy Explor. Exploit., 39(3): 717–737 **(21 pages)**.

He, J.; Mahadevan, A., (2021). How the source depth of coastal upwelling relates to stratification and wind. J. Geophys. Res.: Oceans, 126(12): 1–19 **(19 pages).**

Hosseini, S. T.; Stanev, E.; Pein, J.; Valle-Levinson, A.; Schrum, C., (2023). Longitudinal and lateral circulation and tidal impacts in salt-plug estuaries. Front. Mar. Sci., 10: 1–20 **(20 pages).**

Huang; Y.; Li; G., (2024). Research on tidal energy prediction method based on improved time-varying filter-empirical mode decomposition and confluent double-stream neural network. Ocean Eng., 312(P3): 1-20 **(20 pages)**.

Jeon, W.H.; Lee, S.H.; Moon, H.S.; Kim, Y.; Chang, S.W.; Hwang, S., (2024). Impacts of pumping on the spatiotemporal dynamics of a fresh-saline water mixing zone in a coastal lagoon-aquifer system. J. Hydrol.: Reg. Stud., 51: 101657 **(17 pages).**

Johnston, T.M.S.; Colin, P.L., (2022). Upwelling and downwelling driven by the North Equatorial Countercurrent and internal waves at Hatohobei Island and Helen Reef, Palau. J. Geophys.

Res.: Oceans, 127(2): 1–18 **(18 pages).**

Kersten, M.; Bigalke, M.; Sieber, M.; Wiggenhauser, M., (2022). Cadmium isotope fractionation in an intertidal soil induced by tidal pumping. Environ. Adv., 8: 100182 **(7 pages).**

Kurniawan, A.; Khakhim, N.; Hardjo, K.S.; Santoso, A.I.; Pranowo, W.S., (2021). Constructing an imaginary wall in the ocean: A technical cartography study on the delimitation of maritime boundaries in the provinces of South Sumatra and Bangka Belitung Islands based on GIS. ASEAN J. Sci. Technol. Dev., 38(2): 51–58 **(8 pages).**

Kusumawardani, N.; Djamaluddin, R.; Angmalisang, P.A.; Manu, L.; Pelle, W.E., (2024). Characteristics of sea surface current during the second transitional monsoon in the Bangka Strait, North Sulawesi, Indonesia. Aquatic Sci. Manage., 12(1): 7–13 **(7 pages).**

Leclercq; T.; Chavanne; C.; Larouche; P., (2024). Upwellings and downwellings on the edge of the Gaspé Current: Observations and processes. Reg. Stud. Mar. Sci., 69:1-12 **(12 pages).**

Li, H.; Guo, P.; Liu, G.; Suo, A.; Zhou, W.; Yue, W.; Jiao, M.; Zhang, L., (2024). Numerical study of the upwelling and downwelling effects of artificial reefs along tidal cycles in the Pearl River Estuary. J. Environ. Manage., 365:1-15 **(15 pages**)

Liu, Y.; Jiao, J.J.; Liang, W.; Luo, X., (2017). Tidal pumping-induced nutrients dynamics and biogeochemical implications in an intertidal aquifer. J. Geophys. Res.: Biogeosci., 122(12): 3322–3342 **(21 pages).**

Lorente, P.; Piedracoba, S.; Montero, P.; Sotillo, M.G.; Ruiz, M.I.; Álvarez-Fanjul, E., (2020). Comparative analysis of summer upwelling and downwelling events in NW Spain: A model-observations approach. Remote Sens., 12(17): 1-32 **(32 pages).**

Malik, K.; Pranowo, W.S.; Sukoco, N.B.; Adrianto, D.; Setiyadi, J.; Handoko, D., (2023). Hydrodynamic characteristics of the Lombok Strait during the 2022 west monsoon peak and estimation of ocean current power generation potential. Comput. Exp. Res. Mater. Renew. Energy. 6(2): 72-88 **(16 pages).**

Martín, J.; Alonso, G.; Dragani, W.; Meyerjürgens, J.; Giesecke, R.; Cucco, A.; Fenco, H., (2023). General circulation and tidal wave propagation along the Beagle Channel. J. Mar. Syst., 240: 103889 **(15 pages).**

Mustikasari, E.; Dewi, L.C.; Heriati, A.; Pranowo, W.S., (2015). Pemodelan pola arus barotropik musiman 3 dimensi (3D) untuk mensimulasikan fenomena upwelling di perairan Indonesia. J. Segara, 11(1): 25-35 **(21 pages).**

Nakanowatari, T.; Nakamura, T.; Mitsudera, H.; Nishioka, J.; Kuroda, H.; Uchimoto, K., (2021). Interannual to decadal variability of phosphate in the Oyashio region: Roles of wind-driven ocean current and tidally induced vertical mixing in the Sea of Okhotsk. Prog. Oceanogr., 197: 102615 **(16 pages).**

Neill, P.; Hashemi, R.M., (2018). Fundamentals of ocean renewable energy: Generating Electricity from the Sea. Elsevier.

Nugroho; D.; Koch-Larrouy, A.; Gaspar, P.; Lyard, F.; Reffray, G.; Tranchant, B., (2018). Modelling explicit tides in the Indonesian seas: An important process for surface sea water properties. Mar. Pollut. Bull., 131: 7–18 **(12 pages)**.

Orhan; K.; Mayerle, R., (2020). Potential hydrodynamic impacts and performances of commercial-scale turbine arrays in the Strait of Larantuka, Indonesia. J. Mar. Sci. Eng., 8(3): 0223 **(16 pages).**

Pamungkas, A.; Husrin, S., (2020). Pemodelan sebaran sedimen tersuspensi dampak penambangan timah di perairan Bangka. J. Ilmu Teknol. Kelautan Trop., 12(2): 353–368 **(16 pages).**

Podymov, O.I.; Ocherednik, V.V.; Silvestrova, K.P.; Zatsepin, A.G., (2023). Upwellings and downwellings caused by mesoscale water dynamics in the coastal zone of northeastern Black Sea. J. Mar. Sci. Eng., 11(8): 1628 **(17 pages).**

Pranowo, W.S.; Puspita, C.D.; Bramawanto, R.; Adi, R.A.; Kusumawardani, A.R.T.D., (2014). Dinamika arus dalam mendukung perikanan budidaya laut di Teluk Bone. Harpodon Borneo, 7(2): 135 -152 **(18 pages).**

Rahuna; D.; Erwandi; Kasharjanto, A.; Suyanto, E. M.; Mintarso, C. S. J., (2023). Experimental study on hydrodynamic aspects of turbine which convert hydrokinetic and potential coastal wave energy. IOP Conf. Ser.: Earth Environ. Sci., 1166(1): 012021 **(8 pages)**.

Sabhan; Pranowo, W.S.; Purba, M.; Koropitan, A.F., (2020). Model perpindahan vertikal massa air oleh interaksi arus dan topografi di Teluk Palu. Positron, 10(1): 42–51 **(10 pages).**

Sánchez-Garrido; J. C.; Naranjo, C.; Macías, D.; García-Lafuente, J.; Oguz, T., (2015). Modeling the impact of tidal flows on the biological productivity of the Alboran Sea. J. Geophys. Res. Ocean., 120(11): 7329–7345 (17 pages).

Smith, M.J.D., (2021). Statistical Analysis Handbook: A comprehensive handbook of statistical concepts, techniques and software tools. The Winchelsea Press.

Song, Y.; Haidvogel, D., (1994). A semi-implicit ocean circulation model using a generalized topography-following coordinate system. J. Comp. Phys., 115(1): 228–244 **(17 pages)**.

Stevens; C. L.; Smith; M. J., (2016). Turbulent mixing in a stratified estuarine tidal channel: Hikapu Reach, Pelorus Sound, New Zealand. N. Z. J. Mar. Freshw. Res., 50(4): 485–505 **(21 pages)**.

Tiatama; S. H.; Atmodjo, W.; Widiaratih, R., (2024). Analisis keterkaitan fenomena supermoon terhadap komponen pasang surut di perairan Semarang, Jawa Tengah. Indones. J. Oceanogr., 6(2): 114–120 (7 pages).

Trautman, N.; Walter, R.K., (2021). Seasonal variability of upwelling and downwelling surface current patterns in a small coastal embayment. Cont. Shelf Res., 226: 104490 **(12 pages).**

Wu, L., (2021). Effects of tides and pumping on seawater intrusion in coastal aquifers. 7th Int. Conf. Hydraul. Civ. Eng. Smart Water Conserv. Intell. Disaster Reduct. Forum, ICHCE and SWIDR 2021, 1795–1800 **(6 pages)**.

Xiao, C.; Fan, W.; Qiang, Y.; Xu, Z.; Pan, Y.; Chen, Y., (2018). A tidal pump for artificial downwelling: Theory and experiment. Ocean Eng., 151: 93–104 **(12 pages).**

Xu, Y.; Liu, X.; Zhou, F.; Chen, X.; Ye, R.; Chen, D., (2023). Tide-induced upwelling and its three-dimensional balance of the vertical component of vorticity in the wider area of the Bohai Strait. J. Mar. Sci. Eng., 11(9): 1-20 **(20 pages).**

Xu; H.; Wang; G.; Huang; Z.; Su; Y.; Bai; Y.; Zhang; J., (2023). Hydrodynamic interactions between tide and runoff in the Luanhe Estuary in Bohai Sea, China: From aquaculture reclamation to restoration. Ocean Coast. Manage., 239: 1-18 **(18 pages)**.

Yasra, E.; Pranowo, W.S.; Subardjo, P.; Ismunarti, D.H.; Sukoco, N.B., (2022). Eksperimen numerik hidrodinamika 3-dimensi terhadap sistem diskritisasi hybrid dan sigma perairan Selat Capalulu Maluku Utara. J. Chart Datum. 8(1): 1–14 **(14 pages).**

Yin; M.; Cao; H.; Zhao; W.; Wang; T.; Huang; W.; Cai; M., (2022). Tide-driven microplastics transport in an elongated semi-closed bay: A case study in Xiangshan Bay, China. Sci. Total Environ., 846: 157374 **(14 pages)**.

Yu; Q.; Wang, Y.; Gao, J.; Gao, S.; Flemming, B., (2014). Turbidity maximum formation in a well-mixed macrotidal estuary: The role of tidal pumping. J. Geophys. Res. Ocean., 119(11): 7705–7724 (20 pages).

Zamani, B.; Koch, M., (2020). Comparison between two hydrodynamic models in simulating physical processes of a reservoir with complex morphology: Maroon Reservoir. Water. 12(3): 1-24 **(24 pages).**

Zhao; Y.; Deng; Z.; Yu; T.; Wang; H., (2019). Numerical Study on Tidal Mixing in the Bohai Sea. Mar. Geod., 42(1): 46–63 **(18 pages).**

Zhao, C.; Daewel, U.; Schrum, C., (2019). Tidal impacts on primary production in the North Sea. Earth Syst. Dynam., 10(2): 287–317 **(31 pages).**

Zhao, F.L.; Qiu, B.Y.; Wang, H.J.; Yan, T.X., (2023). Energy saving based on a multi-objective optimization model of the tidal pumping station along the coastal area. J. Clean. Prod., 421: 138513 **(20 pages).**

Zhou, X.; Zhu, G.; Hu, S. (2020). Influence of tides on mass transport in the Bransfield Strait and the adjacent areas, Antarctic. Polar Sci., 23: 1-12 **(12 pages).**

Zou; T.; Gu; Y.; Liu; H.; Lin; Y.; Zhang; L.; Zhang; Y., (2024). High-resolution 3D hydrodynamic modeling and comprehensive assessment of tidal current energy resources. Ocean Eng., 313(P2): 1-16 **(16 pages)**.

Zubir, Z., (2015). Peranan Selat Bangka sebagai pintu gerbang dunia maritim Kota Palembang. J. Penelitian Sejarah dan Budaya. 1(2): 248–263 **(16 pages).**

AUTHOR (S) BIOSKETCHES

Pranowo, W.S., Ph.D., Adjunct Professor, [1]Study program of Oceanography, Indonesia Naval Postgraduate Military Service School (STTAL), Ganesha Street No. 1, West Kelapa Gading, Jakarta, Indonesia. [2]Research Center for Climate and Atmosphere (BRIN), B.J. Habibie Building Science and Technological Park, South Tangerang City, Banten, Indonesia. [3]Korea-Indonesia Marine Technology Cooperation and Research Center (MTCRC), Jakarta, Indonesia
- Email: *widodo.pranowo@gmail.com*
- ORCID: 0000-0002-5798-4181
- Web of Science ResearcherID: P-8252-2017
- Scopus Author ID: 24802605300
- Homepage: https://sttal.ac.id/direktorat/pasca-sarjana/oceanography/

Malik, K., B.Eng., Lieutenant Junior Grade, [1]Study program of Oceanography, Indonesia Naval Postgraduate Military Service School (STTAL), Ganesha Street No. 1, West Kelapa Gading, Jakarta, Indonesia. [2]Hydro-Oceanography Center, Indonesian Navy, Jl. Pantai Kuta V No. 1, East Ancol, North Jakarta.
- Email: *Kurnia.malik@gmail.com*
- ORCID: 0009-0001-4243-1672
- Web of Science ResearcherID: NA
- Scopus Author ID: 59278796900
- Homepage: https://sttal.ac.id/direktorat/pasca-sarjana/oceanography/

Adrianto, D., Ph.D., Captain. [1]Hydro-Oceanography Center, Indonesian Navy, Jl. Pantai Kuta V No. 1, East Ancol, North Jakarta. 2Study program of Oceanography, Indonesia Naval Postgraduate Military Service School (STTAL), Ganesha Street No. 1, West Kelapa Gading, Jakarta, Indonesia.
- Email: *aqilaadrianto@gmail.com*
- ORCID: 0000-0001-5098-2143
- Web of Science ResearcherID: NA
- Scopus Author ID: 57203358477
- Homepage: https://sttal.ac.id/direktorat/pasca-sarjana/oceanography/

Kurniawan A., M.Sc., [1]Coastal and Watershed Management Master's Study Program, Faculty of Geography, Universitas Gadjah Mada, Jl. Kaliurang, Sekip Utara, Bulaksumur Sinduadi Sleman, Sendowo, Sinduadi, Kec. Mlati, Kabupaten Sleman, Daerah Istimewa Yogyakarta, Indonesia. [2]Study program of Oceanography, Indonesia Naval Postgraduate Military Service School (STTAL), Ganesha Street No. 1, West Kelapa Gading, Jakarta, Indonesia.
- Email: *agung.kurniawan.16@mail.ugm.ac.id*
- ORCID: 0000-0002-2441-8706
- Web of Science ResearcherID: NA
- Scopus Author ID: 57372228100
- Homepage: https://sttal.ac.id/direktorat/pasca-sarjana/oceanography/

HOW TO CITE THIS ARTICLE

Widodo, S.P.; Malik, K.; Adrianto, D.; Kurnaiwan, A., (2025). Hydrodynamic simulation experiment of tidal pump in strait waters. Global J. Environ. Sci. Manage., 11(2): 593-608.

DOI: 10.22034/gjesm.2025.02.13

URL: https://www.gjesm.net/article_719921.html

Global J. Environ. Sci. Manage. 11(2): 609-630, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Ecological features of mangroves as indicators of seawater intrusion

Suyadi[1], M. Basyuni[2,3,*], R. Amukti[4], C. Damayanti[5], D. Stokes[5], A. Mubaraq[6], Y.I. Rahmila[1]

[1] *Research Center for Ecology and Ethnobiology, National Research and Innovation Agency, Bogor Indonesia*

[2] *Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Medan 20155, Indonesia*

[3] *Center of Excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia*

[4] *Research Center for Geological Disaster, National Research and Innovation Agency, Bandung, Indonesia*

[5] *Faculty of Science and Engineering, Southern Cross University, Australia*

[6] *Graduate School of Agricultural Science, Faculty of Agriculture, Universitas Sumatera Utara, Medan 20155, Indonesia*

ARTICLE INFO

Article History:
Received 12 November 2024
Revised 03 January 2025
Accepted 04 February 2025

Keywords:
Landscape metrics
Mangrove
Seawater intrusion
Small island
Water quality

DOI: 10.22034/gjesm.2025.02.14

ABSTRACT

BACKGROUND AND OBJECTIVES: Water filters are important ecosystem services in mangroves, playing an essential role in mitigating seawater intrusion and groundwater water management. However, ecological features that can be used as indicators of seawater intrusion in mangroves and the extent of mangroves' role in groundwater quality management in coastal areas are not well identified. This study aimed to determine mangroves ecological features that can serve as indicators of seawater intrusion.

METHODS: A geographic information system and geo-electric method were used, and remote sensing, vegetation survey, sample collection, and interview survey were performed.

FINDINGS: Seawater intrusion is the major problem affecting groundwater quality in coastal areas, especially mall islands. A structural equation model revealed that mean mangrove patch thickness, mean mangrove patch density, soil resistivity, soil porosity, and tree density explained 80–95 percent of the variation in seawater intrusion during wet and dry seasons in the entire study area. Seawater intrusion decreased with increasing mean patch thickness of the mangrove but increased with increasing mangrove patch density. That is, the landscape metrics of mangroves, such as mangrove patch thickness and density, were associated with type when substrate or soil and tree density were good ecological indicators of seawater intrusion. Using landscape metrics as ecological indicators is a relatively quick, cheap, and easy-to-apply method.

CONCLUSION: This study pioneers the use of novel landscape metrics—mean patch thickness and patch density—as ecological indicators of seawater intrusion, providing a quantitative framework that bridges mangrove structural attributes, soil characteristics, and collective influence on groundwater salinity regulation.

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).





NUMBER OF REFERENCES
69



NUMBER OF FIGURES
7



NUMBER OF TABLES
5

*Corresponding Author:
Email: *m.basyuni@usu.ac.id*
Phone: +62853 257 76785
ORCID: 0000-0003-1120-8571

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Groundwater is the primary source of fresh water for the residents of small islands. Fresh water is essential for human life and their activities, such as drinking, bathing, washing, and cleaning, various industries, and agriculture (Shang *et al.,* 2016; Abbasnia *et al.,* 2018; Mello *et al.,* 2018). Water demands for food production, industry, and basic needs have increased (Shang *et al.,* 2016; Gohar *et al.,* 2018). Land use change and associated pollution are affecting groundwater quality, presenting a growing challenge, particularly for small-island-developing states (SIDSs), which were recognized in 1992 at the Earth Summit in Rio de Janeiro, Brazil (Gheuens *et al.,* 2019). According to the United Nations member states, SIDSs comprise 38 states, including Indonesia. As an archipelagic state, Indonesia consists of 17,504 islands, 77 percent (%) of which are categorized as small islands <2000 square kilometers (km^2) in size and most of which are located in eastern Indonesia, including Ambon Island (Lukman, 2021). Small islands are characterized by limited groundwater resources. They are generally vulnerable to environmental and socio-economic change and considerably affected by climate change (Gohar *et al.,* 2018; Gheuens *et al.,* 2019). The most common environmental threats to groundwater resources in coastal regions are seawater intrusion and anthropogenic pollution (Kura *et al.,* 2015; Vann *et al.,* 2020). Seawater intrusion is the landward incursion of seawater, seeping into terrestrial groundwater supplies and increasing salinity (Hilmi *et al.,* 2017). Population growth (and associated changes in land use), change in precipitation patterns, and sea-level rise are all drivers of seawater intrusion. Threats to groundwater supplies likely increase because of the continued expansion of urban settings, coastal development, and climate change (Ketabchi *et al.,* 2016; Gheuens *et al.,* 2019; Vann *et al.,* 2020). The potential impact can be devastating to small-island communities, which are subjected to many health problems, increased poverty, human capital loss, and unstable socio-economic and political platforms (Gheuens *et al.,* 2019). Thus, accessible indicators of saltwater intrusion should be identified to support timely and effective management strategies aimed at strengthening water security. As archipelagic states, SIDSs are typically characterized by long coastlines. Indonesia has the second longest coastline as 99,093 kilometers (km) in the world and a large coastal area (Aldrian, 2008; Setiawan *et al.,* 2016). This tropical coastal area is a suitable habitat for mangroves, making Indonesia the largest habitat of mangroves in the world (3,112,989 ha or 23%) and providing habitat for 67% of the world's true mangrove species (Noor *et al.,* 2006; Giri *et al.,* 2011;Thomas *et al.,* 2017). Mangrove forests provide a wide range of valuable ecosystem services (Duke *et al.,* 2007), control biogeochemical cycles, help to reduce pollutant loading, contribute to coastal nutrient cycles, and provide shoreline protection (Nguyen *et al.,* 2012; Lagomasino *et al.,* 2014; Santos *et al.,* 2014; Xiao *et al.,* 2019). Mangroves thrive at seawater–freshwater interfaces and are valuable mitigators of saltwater intrusion into terrestrial groundwater. The site-specific coverage of mangroves and associated vegetative metrics may provide insights into the risk of saltwater intrusion. Hilmi *et al.* (2017) established the importance of mangroves in mitigating seawater intrusion but did not quantify how structural characteristics, such as patch thickness, influence this process. Xiao *et al.* (2019) highlighted mangroves' role in nutrient cycling but lacked a focus on groundwater salinity regulation. As such, further study is required to explore the influence of geomorphic factors and correlations among mangrove metrics to develop a protocol for identifying sites of high risk to saltwater intrusion. Mangrove habitats can be described or categorized using vegetative and landscape metrics (Horstman *et al.,* 2018; Suyadi *et al.,* 2018a; Damayanti *et al.,* 2020). "Patch size" is the smallest level of heterogeneity in a landscape, which is commonly used in spatial metric analysis. It is defined as a single block of pixels that are spatially connected to each other (McGarigal *et al.,* 2012). A "forest patch" is commonly used as a proxy to assess forest degradation and fragmentation (Riitters *et al.,* 2000). Landscape metrics, such as patch size and shape index, are influenced by the characteristic and distribution of sediments or mangrove substrates (McGarigal *et al.,* 2012; Suyadi *et al.,* 2018a). Seawater intrusion is commonly detected using geo-electrical resistivity surveys or by collecting groundwater from wells. Well water sampling collects detailed information on salinity level and freshwater–seawater interactions (Chen *et al.,* 2018; Vann *et al.,* 2020). Seawater intrusion is influenced by soil properties, such as soil texture (gravel, sand, silt, and clay). The rate of organic matter breakdown is

then linked to microbial activity, which in turn can be altered by seawater intrusion (Weston *et al.,* 2011). Furthermore, mangrove zonation and distribution are influenced by soil type (Duke *et al.,* 2007; Suyadi, 2009). Interactions among soil type, biogeochemical cycles, and mangrove habitat characteristics imply that these ecological indicators should be identified and the extent of mangroves' role in mitigating seawater intrusion should be further assessed. A combination of remote sensing (RS), vegetation field surveys, geo-electrical resistivity survey, soil sampling, and water sampling was used in achieving these objectives, providing a suite of ecological indicators that can be readily mapped, and assessing locations at high risk of saltwater intrusion. In addition, strategies for managing water and coastal areas and mitigating seawater intrusion for small-island communities have been enhanced. This study addresses these gaps by developing and validating specific landscape metrics as indicators of seawater intrusion and exploring their interaction with substrate properties to provide a mechanistic understanding of mangrove functionality in groundwater salinity regulation. The aim of this study is to identify the key ecological indicators of seawater intrusion and to assess the role of mangrove in limiting seawater intrusion in a small island setting. The specific objectives of the study are as follows: 1) to assess the relationship between mangrove landscape metrics and soil properties (soil texture, soil resistivity, and soil porosity) and determine any correlation with terrestrial groundwater salinity (seawater intrusion) in wet and dry seasons and 2) to assess and map the health and spatial characteristics of fringing mangrove forests around Ambon Bay and the water quality and extent of seawater intrusion of groundwater in coastal areas. This study was conducted in Ambon Bay, Maluku, Indonesia, in 2022.

MATERIALS AND METHODS

Study area

Ambon is a small island (80,390 ha; located in eastern Indonesia; 3° 46′ 07.6′′ S, 127° 56′ 26.4′′ E to 3° 31′ 16.7′′ S, 128° 21′ 07.5′′ E). It is the capital city of Maluku Province and the most populated island in the eastern part of Indonesia. Most of the population lives in the coastal area surrounding Ambon Bay and mostly concentrated to the north and south of the bay (Fig. 1). Ambon Bay consists of Inner Ambon Bay (IAB)

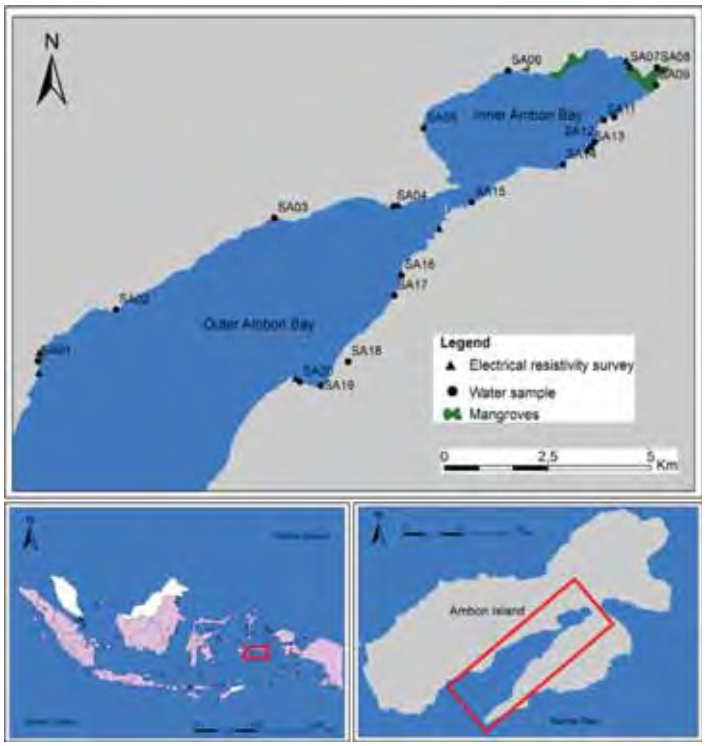


Fig. 1: Geographical location of the study area in Ambon Bay, Maluku, Indonesia

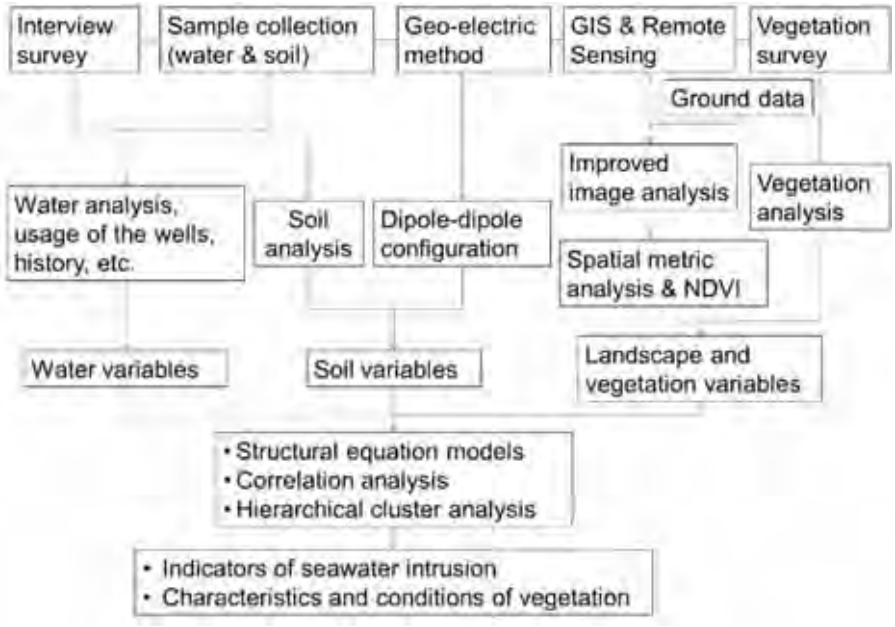


Fig. 2: Combination of some methods applied in this study to achieve the objectives.

and Outer Ambon Bay (OAB). IAB is a semiclosed bay separated by a shallow and narrow sill, and OAB is an open bay and directly connected to Banda Sea. The tide in Ambon Bay (IAB and OAB) ranges from 0.28 m to 2 meters (m) (mean, 1.01 m), with tidal currents of 8.3–29 cm at low tide and 9.0–50.0 cm/s at high tide. Water temperatures in Ambon Bay (IAB and OAB) fluctuate between 27.7 °C and 31.2 °C (mean, 30.5 °C), and salinity is 33.3–34.2 per mille (‰; mean, 33.78 ‰). Tide height, current, and salinity in IAB are lower than those in OAB (Gemilang *et al.,* 2017; Ondara *et al.,* 2017). Mangrove habitat is mostly concentrated in IAB because of marine conditions (e.g., current, tidal), and the geomorphological condition of IAB is more suitable for mangroves (Suyadi, 2009).

Data and sample collections

The study applied a geographic information system (GIS) and a range of methods, such as RS, vegetation surveys, geo-electric mapping, and sample (water and soil) collection followed by interview surveys (Fig. 2), which are required in obtaining spatial data, soil- and water-related data, vegetation, soil resistivity, porosity, and interview data from owners or users of wells.

Sentinel-2 satellite images from 2022 were combined with field mapping using global positioning system (GPS) tracking from 2019 for the generation of a raster dataset of mangroves. An improved image analysis method was applied, which used a combination of integrated parametric (maximum likelihood classification) and nonparametric classifiers (knowledge-based classification; Suyadi *et al.,* 2018b). In image processing, atmospheric correction was first implemented, followed by positional correction and image classification using supervised classification methods: parametric classifier of maximum likelihood classification and nonparametric classification of knowledge-based classification (Suyadi *et al.,* 2018b). This supervised classification, which is recently known as artificial intelligence (AI) or machine learning (ML), require field data for training samples. This classification method was selected because ground data for training samples were available and the method is simple to implement and results in high accuracy. Other image classification methods that incorporate advanced technologies, such as AI, ML, random forest, support vector machines, convolutional neural networks, recurrent neural networks, long short-term memory, and enhanced mangrove index can be applied for image classification but are unsuitable for this study because of the relatively low variation in mangrove vegetation and because the objectives

of the study are extremely complicated. Field data, such as vegetation characteristics and vegetation conditions, were used in determining training samples. Image classification accuracy was assessed using Kappa accuracy followed by field validation, and the ground-truth data of plots and drones were used. The ground-truth data were obtained from 42 sampling points (15 plots and 27 drone data), and drone and sampling plots were circular with diameters of 30 m. Data collected from the plots were GPS coordinates, mangrove species, number of trees, diameter breast height (DBH), canopy coverage, stratum coverage, and photographs. Positional error correction, atmospheric correction, classification correction, and Monte Carlo analysis (Suyadi *et al.,* 2018b) were applied to minimize classification error and to quantify image classification. The raster dataset of mangrove characteristics was exported to Fragstats 4.1. in Geotiff format, and the landscape metrics of mangrove patches were derived. Five landscape metrics were mapped: mean patch size, patch density, mean patch thickness, mean shape index, and largest patch index. These landscape metrics were selected because they are commonly used as spatial indicators for forestry ecological studies, especially for the assessment of forest degradation and fragmentation (Manson *et al.,* 2003; Vaz, 2014; Barau and Qureshi, 2015; Bryan-Brown *et al.,* 2020). The land cover map-2022 was provided by the Ministry of Environment and Forestry of the Republic of Indonesia. The study collected vegetative data from sixty-five 10 m × 10 m mangrove plots. The plots were located along line transects extending toward the sea and extension of the mangrove forest. The plots were 20 m apart along the line transect, and variation in vegetation was captured. The ground-truth plot, line transects (vegetation plots), water wells, and soil sampling points were selected using purposive random sampling, and the following parameters were used: variation in mangrove patch size, variation in vegetation, well age, well depth, and distance from shoreline. Geological map, land cover map, exisiting wells, and knowledge of salinity issue were incorporated for the selection of the point sampling location through purposive random sampling. Each mangrove within a plot was identified to species then measured for DBH at 1.3 m above the ground, tree height, and canopy coverage. Photographs of canopies were taken in nine points inside each plot, and canopy coverage was assessed using ImageJ software. A digital protractor was used in measuring the top tree angle from 10 m distance to the tree and then converted into tree height by using basic trigonometry. Fieldwork and sample collection were conducted between October and December 2020. Water samples were collected from 20 wells around Ambon Bay, which is located less than 200 m from the coastline (Fig. 1). Most of the wells are conventional wells (17), and only three are drilled wells. At the time of sampling, an interview survey was conducting on 20 well owners, and additional information about water color and taste, history, and usage of the wells was obtained. All of the wells are still used by the owners for washing and bathing, and nine wells are used for drinking. The depth of the wells ranges from 1 m to 32 m (mean, 6.85 m) and are located 0–4 m above sea level (masl; mean, 2.2 masl). The age of the wells was between 1 and 90 years (mean, 37 years). Water samples (20 samples) were analyzed in a certified Balai Teknik Kesehatan Lingkungan Laboratory (Registration No. 0022/LPJ/LABLING-1/LRK/KLH from Ministry of Environment and Registration No. LP-241-IDN from National Accreditation Committee). Twelve water quality parameters were measured (Regulation of Ministry of Health No. 32; 2017): salinity, total dissolved solids (TDSs), turbidity, iron, detergent, mineral content, nitrate, manganese, pH, temperature, flavor, and smell. Salinity was measured during the wet and dry seasons to determine seasonal influence on seawater intrusion. Soil samples (85 samples) were collected from plots along the transects and in the bottom of the wells at 0.5 m depth. Fresh soil samples were weighed and dried in an oven at 60 °C until a constant weight was reached. Using the method proposed by Hao *et al.* (2008), we calculated the porosity on the basis of particle density and bulk density. Resistivity data were extracted from field data and data extrapolated using geological maps (Saad *et al.,* 2012; Tjokrosapoetro *et al.,* 1993). Field measurements of resistivity (electrical resistivity) were performed using a single-channel resistivity meter, geo-electric method, and dipole–dipole configuration (Amukti *et al.,* 2023; Damayanti *et al.,* 2020). Measurements were obtained at 11 locations in the study site (Fig. 1), where the transects were perpendicular to the coastline. The transect length was 50–100 m. Electrode recordings were obtained at 10 m intervals

along each transect, and the penetration depth was 25 m. A single-channel resistivity meter used in this study was calibarated regularly before used in the field. In addition, the data are also compared and calibarated with other data (Amukti *et al.,* 2023; Damayanti *et al.,* 2020) and geological map to minimize potential error of resistivity measurements.

Data analysis

Prior to statistical analysis, mangrove landscape metrics data were normalized using the Min-Max normalization approach (Patro and Sahu, 2015). In addition, principal component analysis followed by penalized regression by selection and exclusion of multicorrelated variables were applied to minimize multicollinearity. Normalized difference vegetation index (NDVI) was used in categorizing mangrove health with the method describted by Rotua (2017), based on the ratio of infrared and red band (Green *et al.,* 1998). Vegetation characteristics, including species composition, vegetation structure, zonation, and important value index, were calculated using a formula developed by Cox (1967). On the basis of the standard protocol published by the Ministry of the Environment Republic of Indonesia No. 201 (2004), the status of mangrove vegetation health was determined using tree density and canopy coverage (Dharmawan and Pramudji, 2017). Spearman rank correlation analysis was conducted to assess the correlation of dependent variables (salinity at dry and wet season) with independent variables related with the landscape metrics of mangrove, vegetation, and substrate or soil. Spearman rank correlation analysis was selected because it can measure nonlinear correlation for ordinal data and data with non-nomal disrtribution. Structural equation models (SEMs) were applied to determine the relationship between seawater intrusion (salinity during dry and wet seasons) and independent variables. SEMs are extensions of the general linear model that allows for the simultaneous testing of regression equations and can be used to assess the direct, indirect, and total effects of predicted variables (Schreiber *et al.,* 2006). Thus, SEMs are suitable for quantifying the direct and indirect effects of mangrove metrics and soil properties on seawater intrusion, providing a nuanced understanding of their interactions. Seawater intrusion variables (water salinity at dry and wet season) were grouped through hierarchical cluster analysis, and any relationship with measured independent variables was explored. Kruskal–Wallis test, followed by a Bonferroni post-hoc test, was applied to identify considerable differences in seawater intrusion variables (salinity at dry and wet season) and independent variables among seawater intrusion variables. Lastly, linear regression analysis was applied to assess the relationship between seawater intrusion and independent variables across the groups. Linear regression was suitable with data and can be used to identify key relationship between variables with complex interaction and multiple factors. Interview data were analyzed, and data cleaning was performed by meticulously reading the transcripts. The content, review, and refine themes were comprehensively examined, categorized, and coded, and the results were interpreted. Then, the interview data were used in confirming water and soil sample data.

RESULTS AND DISCUSSION

Groundwater quality and seawater intrusion

In the clean water quality standard provided by the Indonesian Ministry of Health (No. 32, year 2017), groundwater quality in the study area was considered within acceptable levels, except water salinity, especially in the dry season (Table 1). The physical and chemical parameters of ground water, such as turbidity, pH, temperature, flavor, smell, TDS, iron, detergent, mineral content, nitrite, and manganese area were within the range of the clean water quality standard. That is, the groundwater in the study area was relatively unpolluted, but seawater intrusion was observed. This result was confirmed by interview data, which showed that the owner of wells (respondents) still use the water from the wells for washing and bathing. Few well owners used water from the wells for drinking because of seawater intrusion. Another study showed that the quality of water around IAB is within the range of the clean water quality standard, but a water sample from Batumerah Village was contaminated by *Escherichia coli* and had a high total coliform value (Uyara *et al.,* 2017).

Seawater intrusion (water salinity) in 80% of the wells sampled in this study exceeded the clean water quality standard (Table 1). Seawater intrusion increased during the dry season, ranging from 0.29 ppt to 7.4 ppt (mean, 3.51 ± 0.57 ppt) compared with that in the wet season when salinity ranged from

Table 1: Groundwater quality around the study area in Ambon Bay, Maluku

Parameters of water quality	Mean	Min	Max	Quality standard*
Salinity at dry season In part per thousand (ppt)	3.51 ± 0.57	0.29	7.4	<0.5
Salinity at wet season (ppt)	0.25 ± 0.04	0.009	0.74	<0.5
Total dissolved solids Miligram per liter (mg/L)	259.65 ± 39.3	29.1	780	<1000
Turbidity Nephelometric turbidity units (NTUs)	1.55 ± 0.39	0.5	6.03	<25
Iron (mg/L)	0.21 ± 0.07	0.033	1.007	<1
Detergent (mg/L)	0.01 ± 0.002	0.001	0.036	<0.05
Mineral content $CaCo_3$ (mg/L)	147.9 ± 21.82	68	433	<500
Nitrite (mg/L)	0.036 ± 0.03	0.002	0.47	<1
Manganese (mg/L)	0.107 ± 0.033	0.035	0.53	<0.5
pH	6.9 ± 0.3	6.5	7.4	6.5–8.5
Temperature	28.1 ± 0.88	26.1	29.7	Air temperature ± 3
Flavor	No taste	No taste	No taste	No taste
Smell	No smell	No smell	No smell	No smell

*Regulation of Ministry of Health No. 32 year 2017

0.009 ppt to 0.74 ppt (mean, 0.25 ± 0.04 ppt; Fig. 3). Some wells in the south of Ambon Bay and Tawiri (SA1) showed the above guideline values of salinity in both seasons. By contrast, seawater intrusion in Passo (SA8 and SA9), Negeri Lama (SA7), and Waiheru (SA6) were consistently within the acceptable salinity levels for both seasons, whereas other sites showed low salinity (e.g., Passo, Negeri Lama, and Waiheru), which were dominated by mangrove vegetation. This result is in line with spatial data, which showed that south of Ambon Bay had high seawater intrusion in the wet and dry seasons (Fig. 3). Many factors associated with seawater intrusion include dry and wet seasons, forest vegetation, especially mangroves, fresh ground water exploitation, and increase in sea level (Hilmi *et al.,* 2017; Ketabchi *et al.,* 2016; Pires *et al.,* 2017; Tamrin *et al.,* 2021).

This study showed that groundwater resources around Ambon Bay are already impacted by seawater intrusion. Seawater intrusion is one of the most important challenges for water security in many small island (Kura *et al.,* 2015; Gohar *et al.,* 2018; Chen *et al.,* 2018; Gheuens *et al.,* 2019; Vann *et al.,* 2020). Seawater intrusion occurs in other small islands in Indonesia and across the world, for example, Kadatua Island, Sulawesi, Indonesia (Tamrin *et al.,* 2021); Poteran Island, East Java, Indonesia (Tatas *et al.,* 2015); Kamala Beach, Phuket, Thailand (Vann et al., 2020); Kinmen, Xiamen, islands between China and Taiwan (Chen *et al.,* 2018); and Kapas Island, Trengganu, Malaysia (Kura *et al.,* 2015). Small island developing states was identified as high risk states for seawater intrusion which can increase vulnerability to disaster and socio-economic stability (Gheuens *et al.,* 2019; Gohar *et al.,* 2018). Seawater intrusion impacts not only groundwater quality but also groundwater quantity (Tamrin *et al.,* 2021).

Correlation of seawater intrusion with the landscape metrics of mangroves

Image classification showed that the total mangrove area around Ambon Bay was 57.206 ha. The accuray of image classification was 89%, the kappa value was 0.887, and the validation value was 86.7%, all demonstrating that the accuracy of images classification in this study was high (>75%). In addition, 86.7% of the image classification matched the ground data. The uncertainty of image classification was relatively low (6%) because of the this study's improved image analysis method, which increased accuracy and minimized uncertanty to up to 67% relative to that of traditional image analysis (Suyadi *et al.,* 2018b). Mangrove vegetations were distributed in Passo (36,295 ha), Waiheru (13,948 ha), Negeri Lama (2293 ha), and small mangrove patches in the north of Ambon Bay (Fig. 4). Similarly, the area of mangroves in Ambon Bay in 2017 was 57.261 ha and was mainly distributed in the same locations as this study (Rotua, 2017). NDVI analysis produced mangrove vegetation index values of between −0.07

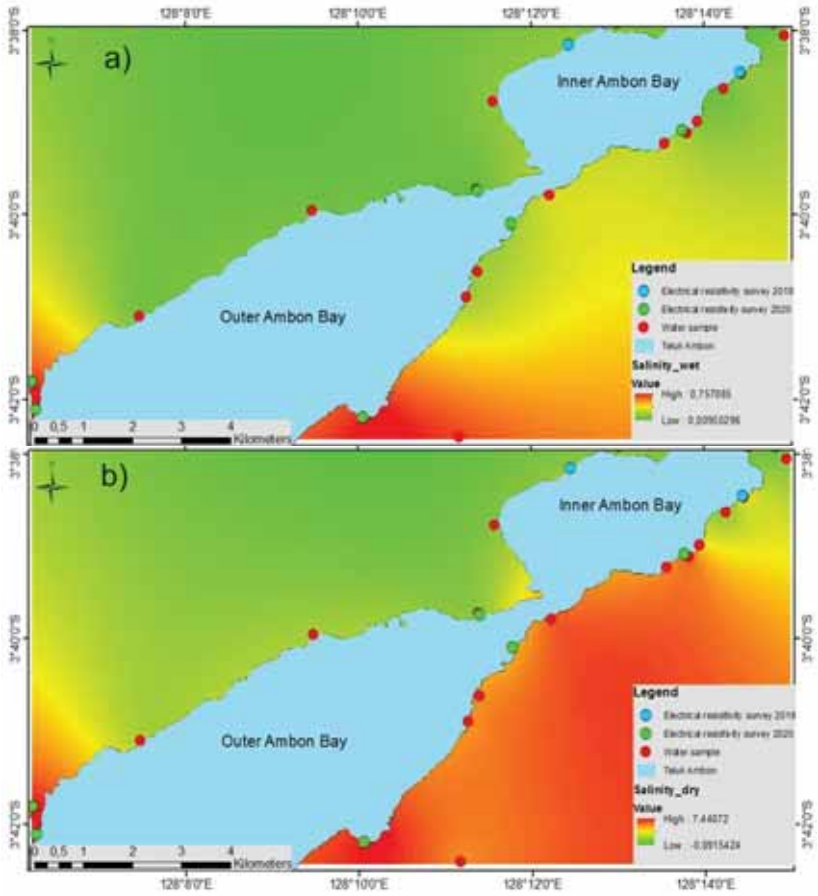


Fig. 3: Seawater intrusion (salinity) during wet season (a) and seawater intrusion during dry seson (b) accros Ambon bay, Maluku

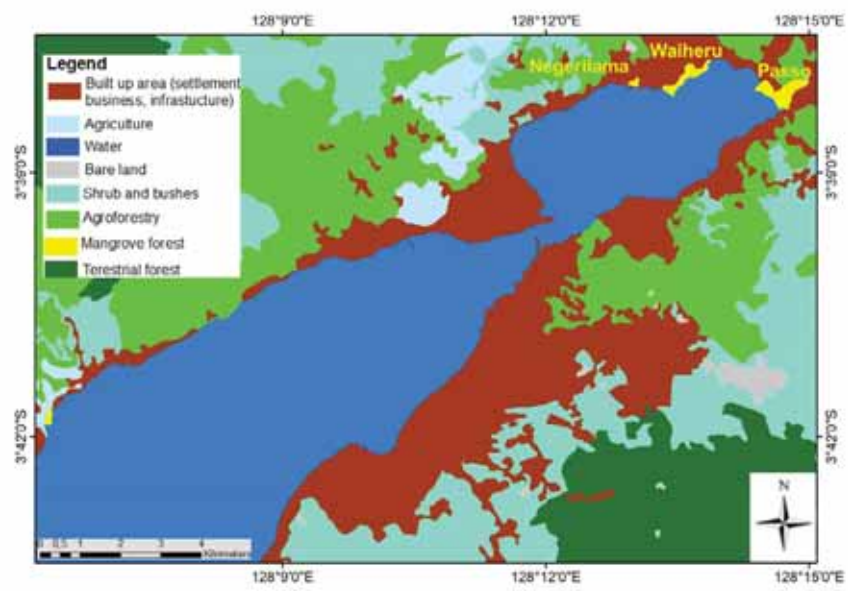


Fig. 4: Mangrove areas and other land cover around Ambon Bay, Maluku

Table 2: Correlation of landscape metrics with seawater intrusion (salinity) during dry and wet season.

Predictors	Mean	Spearman (*rho*) Correlation	
		Salinity at dry season	Salinity at wet season
Mean patch thickness of mangrove (m)	69.82 ± 12.69	−0.85*	−0.53**
Patch density of mangrove (n/ha)	0.03 ± 0.02	0.62*	0.61*
Mean patch size of mangrove (ha)	0.66 ± 0.24	−0.55*	−0.45**
Mean shape index of mangroves	2.22 ± 0.58	0.56*	0.52*
Largest patch index of mangrove	0.89 ± 0.43	−0.54*	−0.48**

*p ≤ 0.01; **p 0.01–0.05

and 0.5 with the highest vegetation index (dense mangroves) measured in Passo, Waiheru, and Negeri Lama. This finding is supported by a previous study showing similar NDVI ranges, that is, the highest vegetation index values were found in Passo, Waiheru, and Negeri Lama (Amukti *et al.,* 2023; Rotua, 2017). Land cover around Ambon Bay was mostly composed of built-up areas followed by agroforestry areas, shrublands, bare lands, and agricultural lands (Fig. 4). Most of the built-up areas were around the coastal area of Ambon Bay, and agroforestry was mostly located in hilly and sloping areas.

Analysis of mangrove landscape metrics showed that the mangroves were predominant in the small patches (mean patch size, 2.66 ± 4.24 ha) and narrow bands along the coastline (mean patch thickness: 69.82 ± 12.69 m). The size of the mangrove patches in Ambon Bay was similar to the size of the mangrove patches in other small islands, such as Karimunjawa, Java, and Batam, Sumatra (KLHK, 2023) but much smaller than the mangrove patches in large islands in temperate regions, such as Auckland, New Zealand (Suyadi *et al.,* 2018a), and tropical regions, such as in Kubu Raya, Kalimantan and Sembilang National Park, Sumatra (KLHK, 2023). Spearman correlation analysis revealed a negative correlation between well water salinity (seawater intrusion) and mangrove mean patch thickness, and the density of mangrove patches was positively correlated with salinity ($p \leq 0.01$). Water salinity in the dry and wet seasons was low at a large mean mangrove patch thickness and increases with mangrove patch density (Table 2). Mean patch thickness ranged from 40.8 m to 540.5 m (mean, 69.82 ± 12.69 m), and patch densities were 0.01–2.4 patches per hectare (mean 0.03 ± 0.02 patches per hectare). The other landscape metrics, that is, mean (mangrove) patch size and largest patch index, showed a negative correlation with salinity, whereas mean patch shape index showed positive correlations (Table 2). Mangrove patch thickness likely reduces saline water ingress by increasing surface roughness and hydrodynamic resistance. The field study using transects revealed that the thickness or width of mangrove vegetation is significantly corelated with seawater intrusion (Damayanti *et al.,* 2020). An equation model also showed that the width of mangrove greenbelt explained 97% of the seawater intrusion (Hilmi *et al.,* 2017).

Correlation of seawater intrusion with mangrove vegetation and its substrate

Field surveys (transects) recorded 15 true mangrove species and one species of mangrove-associated species around Ambon Bay. Most of the mangrove stands in the study area do not display mangrove zonation, except Passo. The landward zone of mangroves in Passo were dominated by nypa (*Nypa fruticans*), and the middle and fringe (seaward) zones were dominated by true mangroves, such as *Rhizopohora* sp., *Excoecaria agallocha*, and *Sonneratia* sp. Mangrove tree density averaged across all sites was 655 stem/ha, and the mean canopy coverage was 19%. High tree density and canopy coverage were measured at Negeri Lama (the highest), Passo, and Waiheru (Table 3). The most dominant species were *Rhizopohora apiculata* (important value index: 60.8%) and *Sonneratia alba* (important value index 19.9%). These two species were distributed across all of the study sites around Ambon Bay, except Tawiri, which was dominated by *Excoecaria agallocha* (important value index, 72.5%). The mean DBH of mangroves was 14.2 ± 12.7 cm, and the mean tree height was 7.8 ± 4.5 m. Compared with another study (Suyadi 2009), the species composition and structure of mangrove vegetation in Ambon Bay within 15 years (2008–2023) were relatively

Table 3: Characteristics and conditions of mangrove vegetation in Ambon Bay, Maluku

Sites	Canopy coverage (%)	Mangrove density (stem/ha)	Health status*	Mean tree diameter (cm)	Mean tree height (m)	Important index	
						Min.	Max.
Passo (SA8)	17	1450	Moderate	19.1 ± 9.9	9.8 ± 3.4	*Brugruiera parviflora* (BP): 11.8	SA: 77.1
Waiheru (SA6)	16	1433	Moderate	10.8 ± 5.4	6.6 ± 2.1	*Rhizopohora stylosa* (RS): 5.4	*Rhizopohora apiculata* (RA): 86.2
Negeri lama (SA7)	20	1580	Moderate	11.8 ± 5.1	6.2 ± 2.3	*Ceriops tagal* (CT): 3.8	RA: 58.9
Halong (SA13)	14	503	Poor	8.8 ± 3.1	5.1 ± 2.1	BP: 4.1	RA: 88.1
Rumah tiga (SA4)	13	526	Poor	9.1 ± 3.5	5.4 ± 2.3	RS: 1.8	RA: 78.9
Tawiri (SA1)	15	243	Very poor	16.2 ± 10	7.8 ± 2.9	*Sonneratia alba* (SA): 25.1	*Excoecaria agallocha* (EA): 72.5
OSM (SA19)	12	108	Very poor	5.8 ± 2.4	4.5 ± 2.7	RS: 3.1	RA: 87.2

*Regulation of Ministry of Environment No 201 year 2004

Table 4: Correlation of mangrove vegetation and substrate (soil) with seawater intrusion (salinity) during dry and wet season

Predictors	Mean	Spearman (*rho*) Correlation	
		Salinity at dry season	Salinity at wet season
Soil resistivity (Ω)	35.20 ± 26.67	−0.90*	−0.76*
Soil porosity (%)	16.84 ± 5.35	0.87*	0.73*
Tree density (stem/ha)	655 ± 32	0.55*	0.53*
Canopy coverage (%)	19	0.46	0.43
Tree high (m)	7.8 ± 4	0.42	0.39
Tree diameter (cm)	14.2 ± 12.7	0.44	0.41

*p ≤ 0.01; **p 0.01–0.05

unchange.

Plants (vegetation) play an important role in slowing groundwater flow, filtering pollutants, and seawater intrusion (Tatas *et al.,* 2015; Hilmi *et al.,* 2017; Pires *et al.,* 2017; Xiao *et al.,* 2019; Ding *et al.,* 2020). Root biomass and roots depth of healthy mangrove described groundwater balance and seawater intrusion (Damayanti *et al.,* 2020; Tatas *et a*l., 2015). Mangrove forests dominated by *Avicennia marina*, *Avicennia alba*, *Rhizophora styllosa*, *Sonneratia alba*, and *Sonneratia caseolaris* have the capability to reduce seawater intrusion (Hilmi *et al.,* 2017). Correlation analysis of this study showed that only tree0 or stem density is slightly correlated with seawater intrusion or water salinity (Table 4). Other vegetation parameters do not correlate with seawater intrusion but is correlated with tree or stem density.

Significant correlations were found between seawater intrusion and substrate of mangroves or soil parameters (soil resistivity and porosity). Soil resistivity was negatively correlated with salinity, whereas soil porosity showed a positive correlation (Table 4). The strength of these correlations was higher in the dry season compared than in the wet season. Soil resistivity was spatially variable, ranging from 0.2 Ω to 75.5 Ω (mean, 35.20 ± 26.67 Ω), as was soil porosity, measuring between 7.7% and 25.9% (mean, 16.84% ± 5.35%). Soil resistivity values were greater at the north of Ambon Bay. Similarly, vegetation cover, especially mangroves, was comparatively higher in the northern regions of Ambon Bay compared with the southern bay. Soil in the north of Ambon Bay was dominated by clay and silt (mud), whereas the substrate sampled in the south of Ambon Bay was dominated by sand

and coral fragments, representing a porous sediment profile. Compared with gravel and sand, clay and silt have high resistivity to seawater and low porosity (Banton *et al.,* 1997; Meyer *et al.,* 2019; Wendroth *et al.,* 2006). The water field capacity of clay and silt are much higher (31%–42%) than sand (10%–18%; Tatas *et al.,* 2015), slowing down saltwater intrusion. Site-specific soil or sediment texture is influenced by vegetation structure and composition, geological conditions, and sedimentation (Tjokrosapoetro *et al.,* 1993; Suyadi, 2009). The root systems of mangroves enhance soil compaction, lowering porosity and permeability and thereby limiting groundwater salinization. Organic matter, such as mangrove root biomass, interacts with soil, altering its porosity and permeability (Xiong *et al.,* 2018). Soil texture in association with mangroves play an important role as a field filter for seawater intruding into groundwater.

Ecological features of mangroves as indicators of seawater intrusion

The SEM revealed that two landscape metrics (mean mangrove patch thickness [p = 0.01] and mean mangrove patch density [p = 0.025]), one vegetation descriptor of tree density (p = 0.025), and the two substrate or soil descriptors (soil resistivity [p = 0.001] and soil porosity [p = 0.001] explained 80%–95% of the variation in seawater intrusion in the wet and dry seasons in all study sites (r^2 = 0.95, p = 0.001 and r^2 = 0.80, p = 0.001; Fig. 5). High patch density correspond (positively correlated) with high seawater intrusion because a high patch density indicates that a mangrove forest is highly fragmented into small mangrove patches. Soil porosity in the fragmented mangrove forest is higher than nonfragmented forest or areas with good mangrove conditions (Banton *et al.,* 1997; Hilmi *et al.,* 2017; Mello *et al.,* 2018; Meyer *et al.,* 2019; Pires *et al.,* 2017; Wendroth *et al.,* 2006). The root biomass and root depth of fragmented mangrove forest (high patch density) is lower than nonfragmented mangroves. Good mangrove coniditons are high mangrove patch tickness, high tree density, and high biomass of roots associated with a mud-dominated substrate which typically shows high resistivity to seawater intrusion (Banton *et al.,* 1997; Meyer *et al.,* 2019; Wendroth *et al.,* 2006). Mean patch thickness, tree density, and soil resistivity negatively explains sea water intrusion. By contrast, mean patch density and soil porosity positively explain sea water intrusion.

The predictors (indicators) of seawater intrusion (patch thickness, patch density, tree density, soil resistivity, and soil porosity) are also explained by other parameters, such as largest patch index, mean

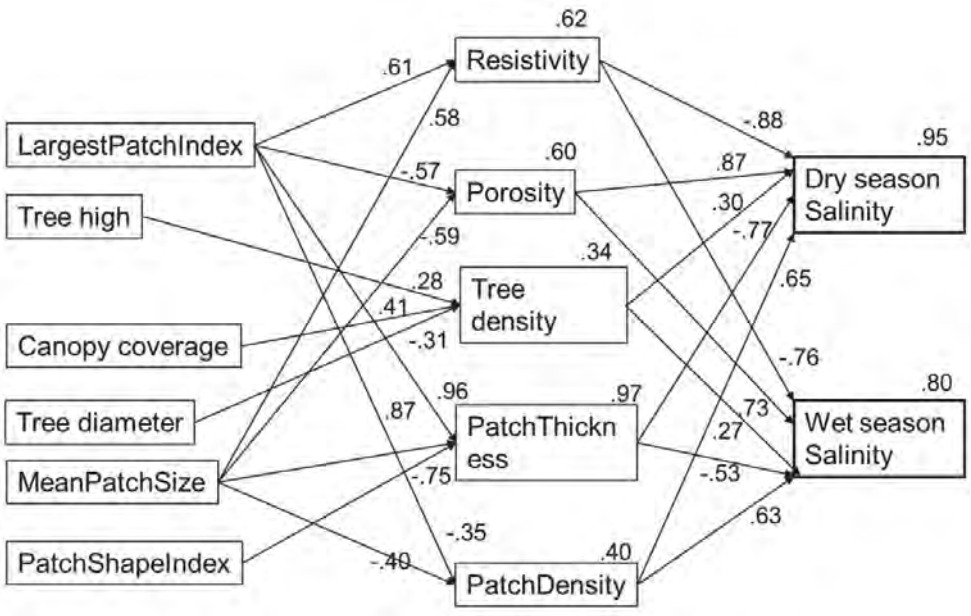


Fig. 5: Structural equation model showing the predictors (indicators) of seawater intrusion (salinity) in dry and wet seasons

patch size, patch shape index, tree height, tree diameter, and canopy coverage, which show positive and negative correlations (Fig. 5). For example, mean patch thickness was positively correlated with largest patch index and mean patch size but negatively correlated with patch shape index. Soil porosity and soil resistivity were closely linked to largest patch index and mean patch size (Fig. 5). This result indicates that patch thickness, patch density, tree density, soil resistivity, and soil porosity are the direct ecological indicators of seawater intrusion and are influenced by indirect factors or parameters. Hierarchical cluster analysis grouped seawater intrusion in the study area into three groups: groups 1 (low seawater intrusion area: mean 0.7 ± 0.4 ppt), 2 (moderate seawater intrusion area: mean 1.4 ± 0.3 ppt), and 3 (high seawater intrusion area: mean 5.5 ± 1.3 ppt; Fig. 6). This result supported by Kruskal–Wallis analysis showed that seawater intrusion in group 3 was significantly higher than those in groups 2 ($p = 0.014$) and 1 ($p = 0.018$), $\chi 2\ (2) = 8.75$, $p = 0.011$. Group 1 (low seawater intrusion area) was mostly located in the northeast of Ambon Bay, particularly in Passo, Waiheru, and Negerilama. The area is the largest habitat of mangrove in the Bay (Figs. 3 and 4). By contrast, mangrove in the south of Ambon Bay (the high seawater intrusion area/group 3) was extremely limited. The mangroves is heavily fragmented into single trees or extremely small mangrove patches.

The three groups of seawater intrusion areas (Fig. 6) corresponded with mangrove landscape metrics, mangrove vegetation, and their substrate or soil (Table 5). All the parameters of landscape metrics showed heavy mangrove fragmentation in the high seawater intrusion area (group 3), moderate fragmentation in the area of group 2, and low fragmentation in the low seawater intrusion area (group 1; Table 5). Further, vegetation analysis was performed according to the Decree of the Minister of Environment of Republik of Indonesia No. 201 (2004), which provides mangrove health standard. The condition of mangrove vegetation was moderate

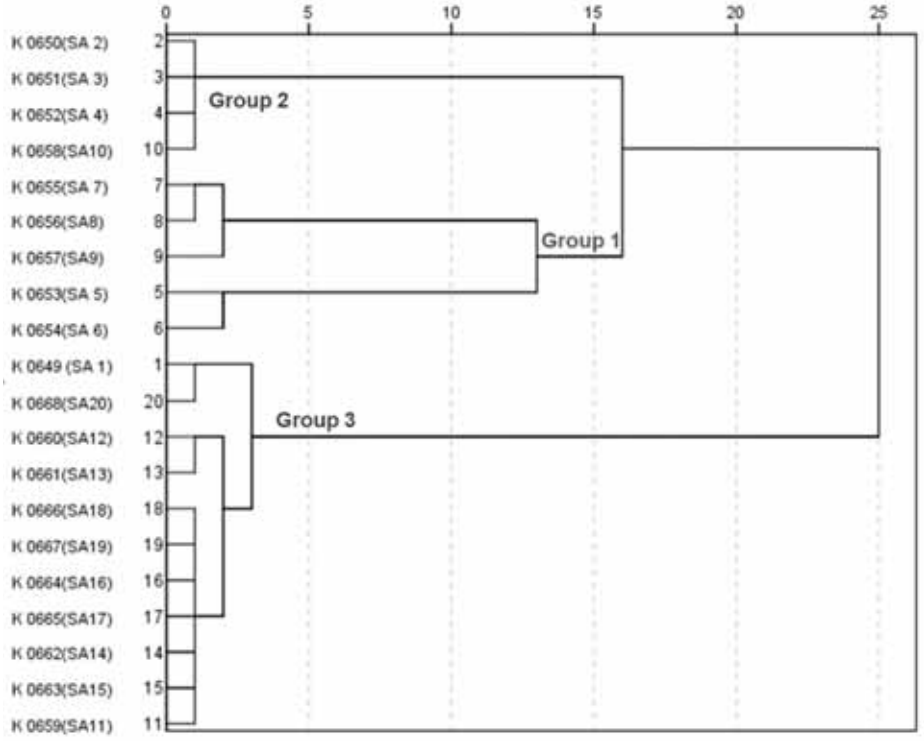


Fig. 6: Hierarchical cluster analysis grouped seawater analysis into three groups: group 1, moderate seawater intrusion (mean 1.4 ± 0.3 ppt); group 2, low seawater intrusion (mean 0.7 ± 0.4 ppt); and group 3, high seawater intrusion (mean 5.5 ± 1.3 ppt)

Table 5: Variation of landscape metrics of mangrove, mangrove vegetation, and its substrate/ soil in three groups of seawater intrusion areas

Parameters	Group 1	Group 2	Group 3
Seawater intrusion (ppt)*	1.4 ± 0.3	0.7 ± 0.4	5.5 ± 1.3
Mean resistivity (Ω)	66.1 ± 23.1	55.5 ± 5.4	14.7 ± 9.0
Porosity (%)	11.2 ± 4.3	12.7 ± 0.8	20.8 ± 2.9
Mean patch size (ha)	1.92 ± 4.4	8.04 ± 3.7	0.49 ± 1.5
Thickness patch (m)	13.15 ± 9.1	54.98 ± 3.4	6.26 ± 4.3
Patch density (patches per hectare)	0.01 ± 0.01	0.02 ± 0.003	0.05 ± 0.02
Shape index	2.47 ± 0.3	1.57 ± 0.5	2.44 ± 0.5
Largest patch index	0.88 ± 0.3	1.41 ± 0.2	0.64 ± 0.7
Fragmentation	Low	Moderate	Heavy
Mangrove vegetation*	Moderate	Poor	Very poor

*Decree of the Minister of Environment No. 201 of 2004

in the area with low seawater intrusion (group 1) and high in the area with high seawater intrusion area (group 3; Table 5). Soil resistivity and soil porosity were also significantly different among tree groups of seawater intrusion areas, $\chi 2$ (2) = 8.82, p = 0.011 and $\chi 2$ (2) = 8.95, p = 0.011, respectively. High seawater intrusion corresponded with heavy mangrove fragmentation (patch thickness of 6.26 ± 4.3 m and patch density of 0.05 ± 0.02 patches per hectare) and very poor mangrove vegetation (Tables 3 and 5). This result indicates that the critical thresholds for mangrove patch thickness and patch density in this study were 6.26 ± 4.3 m and 0.05 ± 0.02 patches per hectare, respectively. Local environmental conditions, mangrove ecosystem characteristics, and level of ground water extraction may play important roles in determining critical thresholds. For example, patch thickness falls below 50 m, and tidal forces and storm surges are more likely to breach the mangrove barrier, promoting the intrusion of seawater into coastal groundwater systems (Das and Crépin, 2013; Zhang *et al.,* 2012). Similarly, a canopy density below 70% compromises the ability of mangroves to reduce soil salinity and maintain adequate hydrological conditions for coastal ecosystems (Danielsen *et al.,* 2005; Krauss *et al.,* 2008). These thresholds align with global studies, indicating that mangrove forests with high structural integrity as defined by patch size and density exhibit high resistance to hydrodynamic forces and good functionality as coastal buffers (Spalding *et al.,* 2010; Lee *et al.,* 2014). For instance, in small-island settings, such as the Philippines, mangrove restoration projects have demonstrated that achieving a minimum thickness of 50–100 m is critical for reducing the impacts of seawater intrusion and ensuring long-term sustainability (Danielsen *et al.,* 2005). These thresholds provide actionable benchmarks for seawater intrusion monitoring using ecological indicators and seawater intrusion mitigation through mangrove restoration. Restoration efforts should prioritize areas where mangrove thickness and density can meet or exceed these critical values, ensuring effective ecological functionality to mitigate seawater intrusion. For degraded areas with suboptimal thresholds, restoration using native species and techniques, such as hydrological restoration, should be implemented to rebuild mangrove cover (Krauss *et al.,* 2008). Furthermore, the regular monitoring of patch metrics and seawater intrusion using RS and field surveys can be used in evaluating seawater intrusion risk and ensuring that restoration projects maintain these critical thresholds over time (Spalding *et al.,* 2010; Zhang *et al.,* 2012).

The regression analysis showed that the correlation of parameters of mangrove landscape metrics, mangrove vegetation, and their substrate or soil with seawater intrusion (salinity) varied among groups of seawater intrusion areas (Fig. 7). A good fit between mangrove patch thickness and seawater intrusion was found in the low- and high-seawater-intrusion areas (groups 1 and 3) during the dry and wet seasons (Fig. 7). Soil resistivity was strongly correlated with seawater intrusion (salinity) in all seawater intrusion areas (groups 1, 2, and 3). This result indicates that the ecological indicators (patch thickness, patch density, tree density, soil resistivity, and soil porosity) can be used in determining seawater intrusion in spesific areas

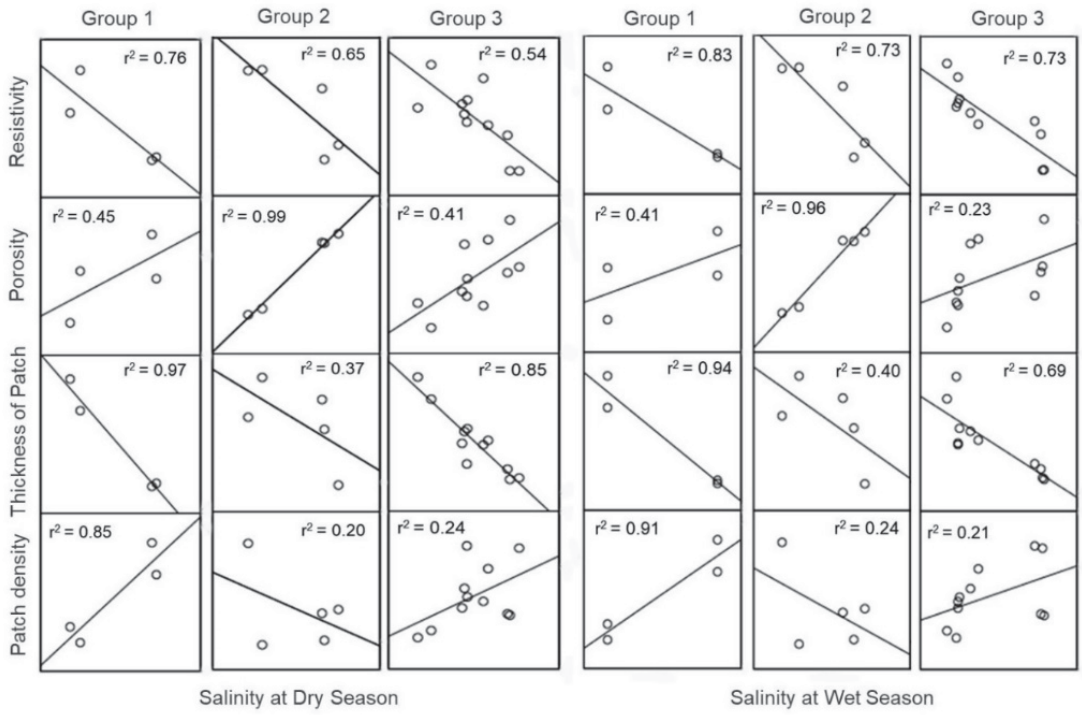


Fig. 7: Correlations of mangrove landscape metrics and mangrove substrate (soil) with seawater intrusion (salinity) in three groups of seawater intrusion areas during dry and wet seasons

or zones. Seawater–groundwater exchange rates in areas or zones where mangrove cover are dominant are much lower than those in areas dominated by other types of land cover, such as agricultural lands, shrublands, and built-up areas or bare lands (Xiao *et al.,* 2018). In addition, fresh groundwater continuously flow to the landward and middle zones of mangroves, serving as an important sink of seawater particles (Xiao *et al.,* 2019).

The limitation of this study is that groundwater extraction was excluded because of data limitation. However, Ambon Bay and mangrove areas (e.g., Passo, Waiheru, and Negeri Lama) are surrounded by built-up areas (housing, commercial, and agriculture areas), and thus the levels of water extraction around Ambon Bay were similar. Incorporating time-series data (monitoring data) with long temporal scale will considerably improve the reliability and clarity of findings related to mangrove ecosystems and seawater intrusion risks. Long-term datasets will capture seasonal and interannual variability in environmental factors, such as salinity, monsoon, season, tidal patterns, and mangrove landscape and vegetation dynamics. For example, time-series satellite imagery integrated with the time-series of field measurements will reveal the patterns of or change in the landscape metrics of mangroves (e.g., patch thickness and patch density) and and the progression of seawater intrusion over time, allowing for the identification of slow-onset processes that short-term studies might miss. Furthermore, incorporating real-time data collection can help to identify fluctuations in or the dynamics of mangrove and seawater intrusion. This approach provides a means for early warning regarding mangrove degradation and seawater intrusion potential. The results of this study demonstrate that landscape scale of mangrove metrics can be used as ecological indicators of seawater intrusion in coastal areas. Mangrove patch thickness and patch density were particularly strong indicators of seawater intrusion around Ambon Bay. However, in some locations, seawater intrusion is exacerbated by sea-level rise (Hilmi *et al.,* 2017; Ketabchi et al., 2016; Pires *et al.,* 2017; Tamrin *et al.,* 2021), which can alter the effectiveness of the proposed ecological indicators

of seawater intrusion. Therefore, large and wide (thick) mangrove patches are crucial to ensuring the efectivness of these ecological indicators. A large and thick mangrove patch with healthy mangrove vegetation is a good sediment trap that can offset the effect of increase in sea level. In addition, habitat shifting and mangrove expansion enable mangroves to be highly effective in adapting to sea-level rise (Duke *et al.,* 2007; Goldberg *et al.,* 2020; Suyadi *et al.,* 2008a). Using these landscape metrics in exploring potential seawater intrusion has many benefits. The integration of field sampling and RS can be applied anywhere, and this approach is relatively quick, cheap, and straightforward. This approach can be applied by policy makers and coastal managers responsible for much of the policy and management of groundwater and mangrove ecosystems. However, skills in the use of GIS and RS are required, and some field skills are needed to derive ground truth from GIS outputs.

Management implications

Some mangrove features have high potential as ecological indicators of seawater intrusion and mangrove forest and play important role in evaluating groundwater quality and availability. However, mangrove forests around Ambon Bay, especially the south of Ambon Bay, were highly fragmented. This condition is indicated by the low mean patch thickness (69.82 ± 12.69 m) and high mangrove patch density (0.03 ± 0.02/ha; Table 2, Fig. 5). All the parameters of landscape metrics showed heavy fragmentation in the south of Ambon Bay (group 3) and relatively low fragmentation in the north of Ambon Bay (group 1; Table 5). The high level of mangrove fragmentation is further supported by the low mean patch size (0.66 ± 0.24 ha), irregular patch shape index (2.22 ± 0.58), and small largest patch index (0.89 ± 0.43). On the basis of the guidelines provided by the Indonesian Ministry of Environment (No 201, 2004), the status of mangrove vegetation health in Ambon Bay was categorized as moderate (group 1, low seawater intrusion areas), poor (group 2, medium seawater intrusion areas), and very poor (group 3, high seawater intrusion areas; Table 5). This descriptive analysis is further supported by NDVI analysis, which showed similar findings. In terms of the NDVI value, mangroves in group 1, which included the low seawater intrusion areas (e.g., Passo, Waiheru, and Negeri Lama) had moderate heatlh status (NDVI, 0.43–0.5), group 2, which are medium seawater intrusion areas, such as Halong (SA13) and Rumah Tiga (SA4), had poor health status (NDVI, 0.22–0.42), and group 3, which had high seawater intrusion areas, such as Tawiri (SA1) and OSM (SA19), had very poor health stauts (NDVI, 0.01–0.21). Another study showed that the mangrove area in Ambon Bay had decreased from 85.689 ha in 1995 to 57.206 ha (Rotua, 2017). Mangrove deforestation and fragmentation not only occurred at the local scale, particularly in Ambon Bay, but also continues to be a national and global issue. Mangrove forest cover worldwide had decreased, and 62% of the mangrove cover had degraded from 2000 to 2016 (Goldberg *et al.,* 2020). Indonesia has one of the highest total areal losses of mangroves and has shown increasing forest fragmentation, and 40% of the country's mangrove forests had been cleared or degraded (Andrew *et al.,* 2015; Murdiyarso *et al.,* 2015; Basyuni and Sulistiyono, 2018; Bryan-Brown *et al.,* 2020). The mangrove deforestation and degradation rate is 14% per year (Giri *et al.,* 2011; Murdiyarso *et al.,* 2015; Thomas *et al.,* 2017. Mangrove deforestation in Indonesia emit large amounts of carbon dioxide (Murdiyarso *et al.,* 2015), and illegal logging has reduced approximately 56% of aboveground biomass in Lubuk Kertang Forest, North Sumatra, for only one year (Basyuni *et al.,* 2025). The high rates of mangrove deforestation and fragmentation in Indonesia will considerably impact groundwater quality by promoting seawater intrusion, particularly in small islands (Hilmi *et al.,* 2017; Pires *et al.,* 2017; Mello *et al.,* 2018; Goldberg *et al.,* 2020). The root causes of mangrove deforestation and fragmentation in Indonesia are illegal logging, pollution (e.g., plastic and oil spil pollution), and mangrove conversion into lands for aquaculture, agriculture, housing, and business construction. The findings of this study highlight the importance of mangrove conservation (law enforcement and strict protection) for remaining mangroves and restoration programs for restoring degraded mangroves. The focus of this study is the development of a massive mangrove greenbelt with optimal patch thickness and density and capability to mitigate seawater intrusion. Implementing strict penalties for illegal logging, expanding protected

mangrove areas, and restoring degraded mangrove are effective strategies for reducing mangrove degradation due to illegal logging and mangrove conversion. These actions should be integrated with community-based mangrove conservation strategies, such as increasing public awareness, providing sustainable alternative livelihoods, and encouraging community participation in reducing pollutants, especially plastic and oil spill. The implementation of laws designed to protect native vegetations, such as mangroves, mangrove restoration, improved soil management practices, and fresh groundwater management are required to prevent potential seawater intrusion (Ellison *et al.,* 2017; Mello *et al.,* 2018; Pires *et al.,* 2017). Law enforcement and mangrove forest protection should be supported by strong and harmonious laws and policies in central and local governments. Strengthening the legal framework through the establishment of mangrove-specific law and policies will fill existing gaps, such as inadequate penalties, insufficient monitoring, and unclear land ownership issues, which often lead to mangrove exploitation. Community-based mangrove conservation and restoration should be legally recognized and supported by laws and policies. Another critical law and policy measure is the integration of mangrove conservation and restoration into climate adaptation and mitigation strategies, such as blue carbon and carbon credit regulation. In addition, some international frameworks, such as the Ramsar Convention on Wetlands and the United Nations Sustainable Development Goals, can guide countries in implementing global best practices for mangrove conservation, strengthen law enforcement mechanisms, enhance funding opportunities, and facilitate cross-border collaboration on conservation and restoration efforts. Mangrove restoration strategies, such as mangrove greenbelt development, are vital to mitigating seawater intrusion and sustaining potable groundwater resources (Hilmi *et al.,* 2017; Pires *et al.,* 2017; Mello *et al.,* 2018). However, the socio-economic status of local communities relies on coastal resources and influences the success of mangrove conservation and restoration. Therefore, ensuring that local communities receive socio-economic benefits from mangrove conservation and restoration is important. Enhanced mangrove forest management, soil management, and mangrove restoration have many benefits because thick and healthy mangroves have numerous essential ecological functions and ecosystem services, such as water filtering, biodiversity maintenance, and climate change mitigation through carbon sequestration (Ellison *et al.,* 2017; Pires *et al.,* 2017; Mello *et al.,* 2018; Jung *et al.,* 2021). Moreover, mangrove conservation and restoration provide direct (e.g., mangrove nursery, mangrove planting, ecotourism, nontimber products, and carbon credit) and indirect (e.g., ecological functions, silvofihsery, fishing ground, and nursery ground) economic implications for communities. Improved soil management is important to ensuring the availability and quality of ground fresh water, controlling erosion and soil vertility, and maintaining soil resistivity. A modeling study showed that forest restoration is achievable and financially feasible (Pires *et al.,* 2017). Climate change adaptation and carbon financing strategies should be integrated to attract funding for mangrove conservation and restoration. Local community organizations and citizen conservation play critical roles in the success of mangrove conservation and restoration. Effective strategies for enhancing community engagement are as follows: 1) improving knowledge and skills needed for mangrove conservation and restoration through training and capacity building, 2) fostering a sense of ownership and accountability through participatory decision-making and stewardship rights and responsibilities over mangrove areas, 3) providing alternative incomes through eco-tourism and sustainable aquaculture practices (e.g., silvofishery), 4) providing education and public awareness especially for children, teenagers, students, and women (mothers), and 5) establishing incentives or payments for ecosystem services or access to carbon financing programs through carbon credits. These strategies can motivate communities to actively contribute to conservation and restoration initiatives. Thus, the proposed solution can be summarized as an integrated approach linking ecological, hydrological, and socioeconomic aspects to improve water sources and mangrove management in small islands. These proposed solutions can be applied to other small islands because most small islands face similar challenges, such as limited resources of groundwater and high

risk of seawater intrusion (Kura *et al.,* 2015; Gohar *et al.,* 2018; Chen *et al.,* 2018; Gheuens *et al.,* 2019; Vann *et al.,* 2020). Small islands have similar environment conditions, such as geomorphological condition, oceanic condition, and coastal conditions, including mangrove type (e.g., carbonate setting). The proposed solutions can be easily scaled up to large coastal areas because most large coastal areas (e.g., coastline area, estuarine area, and riverine area) are good habitats for mangroves.

CONCLUSION

Seawater intrusion poses a considerable threat to groundwater quality in coastal areas, particularly in small-island settings where communities heavily rely on fresh groundwater for daily needs. The findings of this study underscore the critical role of mangrove ecosystems in mitigating seawater intrusion and highlight specific ecological features as reliable indicators. Specifically, landscape metrics, such as mangrove patch thickness and patch density, in conjunction with soil characteristics, such as soil resistivity and porosity, explained up to 80% of the variation in seawater intrusion level in the study area. These relationships reveal the complexity of interactions between vegetative and substrate parameters in controlling groundwater salinity. Seawater intrusion was negatively correlated with patch thickness and soil resistivity, suggesting that thick or wide patches, dense vegetations, healthy mangroves, and compact substrates are effective barriers against seawater ingress. Conversely, a positive correlation with patch density and soil porosity indicates that fragmented mangroves and porous soil exacerbate the issue. These findings provide compelling evidence that conserving and restoring mangrove habitats are needed for sustainable groundwater quality. Mangrove forests around Ambon Bay and many mangroves in other locations in Indonesia were categorized as "unhealthy" because of high fragmentation and low tree density and canopy coverage, reflecting alarming mangrove degradation caused by conversion into other land use types (such as ponds, houses, and business centers), illegal logging, pollution, and unsustainable land-use practices. Effective coastal management strategies are urgently required to address these challenges. Key interventions include the implementation of mangrove greenbelt development, active mangrove restoration programs, and stringent native vegetation protection laws. These measures should be complemented by improved soil management practices to enhance soil resistivity, reduce porosity, and further mitigate the risk of seawater intrusion. The integration of RS and field-based assessments, as demonstrated in this study, provides a cost-effective and scalable approach for monitoring and managing seawater intrusion risk. A more holistic approach for water resource management is needed to secure groundwater availability for future generations, encompassing limiting groundwater extraction, enforcing regulations on coastal development, and promoting community awareness of the ecological and economic benefits of mangroves. Furthermore, future research should explore the long-term impacts of climate change, such as rising sea levels and altered precipitation patterns, on seawater intrusion dynamics in small islands. Integrating ecological, hydrological, and socioeconomic dimensions will ensure comprehensive solutions to the multifaceted challenges posed by seawater intrusion. Mangrove conservation and restoration are indispensable for mitigating seawater intrusion and securing freshwater resources in coastal and island settings. The adoption of evidence-based management practices, informed by ecological indicators, such as those identified in this study, will be crucial for achieving sustainable water security in small-island states, such as Ambon. These efforts must be prioritized to safeguard the livelihood and well-being of coastal communities, ensuring resilience against environmental degradation and climate change. This study advances the theoretical framework of mangrove functionality by demonstrating the importance of landscape metrics in regulating seawater intrusion and bridges gaps in previous research. Future studies should explore the long-term impacts of climate change, such as rising sea levels and altered precipitation patterns, on the efficacy of mangrove metrics in groundwater regulation.

AUTHOR CONTRIBUTIONS

Suyadi contributed in conceptualization, research grant, research design, fieldwork, data analysis, model development, investigation, methodology, writing-original draft, revising, editing, and

visualization. M. Basyuni, contributed in research grant, investigation, drafting, revising, and editing. Debra Stokes, contributed in drafting, revising, and editing. R. Amukti contributed in fieldwork, resistivity and porosity data collection, and geo-electrical data analysis. C. Damayanti contributed in fieldwork, resistivity and porosity data collection, and geo-electrical data analisis. A. Mubaraq, contributed in drafting, revising, and editing. Y.I. Rahmila contributed in drafting, revising, and editing.

ACKNOWLEDGEMENT

This study was supported by Kurita Overseas Research Grant 2020 - Kurita Water and Environment Foundation [Grant number: 20Pid002-UB] Japan and by the RIIM LDPD grant and BRIN [Contract number: B-803/II.7.5/FR/6/2022 and B-1373/III.5/PR.03.08/6/2022]. This study was also supported by e-ASIA Joint Program from Endowment Fund for Education Agency (Lembaga Pengelola Dana Pendidikan), Ministry of Finance, Republic of Indonesia year 2024-2025 [019/E5/PG.02.00/PRPB BATCH 2/2024]. This work was also partly funded by Center of Excellence for Mangrove grants from Ministry of Education, Culture, Research and Technology and Penelitian Kolaborasi Unggulan Universitas Sumatera Utara (PKUU) EQUITY 2023-2024 [91/UN5.2.3.1/PPM/KPEP/2023] from Indonesia Endowment Fund for Education and Directorate Research, Technology, and Community Service, Ministry of Education, Culture, Research and Technology, Republic of Indonesia. Authors also thank to the Research Center for Ecology and Ethnobiology-BRIN, Zen Ladestam Siallagan, Alexander Y. Elake, Christian Jacob, Wempi Barends, Iwan Naroli, and Simon Leatemia for their assistance during field data and sample collection.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
/ha	Per hectare
/sec	Per second
‰	Per mille
^{o}C	Degrees Celsius
BP	*Brugruiera parviflora*
BTKL	Balai Teknik Kesehatan Lingkungan/ Environment health
$CaCo_3$	Calcium carbonate
cm	Centimeter
CT	*Ceriops tagal*
DBH	Diameter breast height
EA	Excoecaria agallocha
e.g.	Exempli gratia
GIS	geographic information system
GPS	Global positioning system
ha	Hectare

IAB	Inner Ambon Bay
km	Kilometer
km²	Square kilometer
masl	Meter above sea level
m	Meter
mg/L	Milligram per litre
NDVI	Normalized difference vegetation index
NTU	Nephelometric turbidity units
OAB	Outer Ambon Bay
PES	Payments for ecosystem services
pH	Potential of Hydrogen
ppt	Part per thousand
RA	*Rhizophora apiculata*
RS	*Rhizophora stylosa*
RS	Remote sensing
SA	*Sonneratia alba*
SEM	Structural Equation Models
SIDS	Small Island Developing States
TDS	Total Dissolved Solids
UN	United Nations
UNSDGs	United Nations Sustainable Development Goals

REFERENCES

Abbasnia, A.; Yousefi, N.; Mahvi, A.H.; Nabizadeh, R.; Radfard, M.; Yousefi, M.; Alimohammadi, M., (2018). Evaluation of groundwater quality using water quality index and its suitability for assessing water for drinking and irrigation purposes: Case study of Sistan and Baluchistan province (Iran). Hum. Ecol. Risk Assess. Int. J., 25(4): 988-1005 **(18 pages).**

Aldrian, E., (2008). Meteorologi Laut Indonesia. Jakarta: Badan Meteorologi dan Geofisika, 1-243 **(243 pages).**

Amukti, R.; Damayanti, C.; Souisa, C.J.; Barends, W.; Suyadi, S.; Adji, A.S.; Elake, A.Y., (2023). Electrical resistivity and vegetation index analysis as indicators of seawater intrusion in Ambon Island. AIP Conference Proceeding, 2601(1): 020010 **(8 pages).**

Andrew, D.O.; Rod, M.C.; Kylie, A.P.; Simon, J.P.; Paul, S.M.; Chantal, M.H.; Brad, R.M.; Simon, A.; David, R.; Russell, C.B.; Thomas, A.S., (2015). Quantifying the conservation value of seascape connectivity: a global synthesis. Global Ecol. Biogeogr., 25(1): 3-15 **(13 pages)**.

Banton, O.; Cimon, M.A.; Seguin, M.K., (1997). Mapping field-scale physical properties of soil with electrical resistivity. Soil Sci. Soc. Am. J., 61(4): 1010-1017 **(8 pages).**

Barau, A.S.; Qureshi, S., (2015). Using agent-based modelling and landscape metrics to assess landscape fragmentation in Iskandar Malaysia. Ecol. Processes. 4(1): 1-11 **(11 pages).**

Basyuni, M.; Amelia, R.; Aznawi, A.; Wirasatriya, A.; Iryanthony, S.; Slamet, B.; Al Mustaniroh, S.; Rahmania, R.; Rahmila, Y.; Sumarga, E.; Larekeng, S.; Salmo III, S.; Kajita, T.; Sivaipram, I.; Ali, H., (2025). Reduction of mangrove carbon stock ecosystems due to illegal logging using a combination of unmanned aerial vehicle imagery and field surveys. Global J. Environ. Sci. Manage., 11(1): 225-242 (**18 pages**).

Basyuni, M.; Sulistiyono, N., (2018). Deforestation and reforestation analysis from land-use changes in North Sumatran Mangroves, 1990-2015. IOP Conference Series: Mater. Sci. Eng., 309: 1-6 (**6 pages**).

Bryan-Brown, D.N.; Connolly, R.M.; Richards, D.R.; Adame, F.; Friess, D.A.; Brown, C.J., (2020). Global trends in mangrove forest fragmentation. Sci. Rep., 10(1): 1-8 **(8 pages).**

Chen, T.T.; Hung, Y.C.; Hsueh, M.W.; Yeh, Y.H.; Weng, K.W., (2018). Evaluating the application of electrical resistivity tomography for investigating seawater intrusion. Electronics. 7(7): 107 **(19 pages).**

Cox, G.W., (1967). Laboratory Manual of General Ecology. MWC. Brown Comp. Publishers, Dubuque, IOWA **(276 pages).**

Damayanti, C.; Amukti, R.; Suyadi, S., (2020). Potensi Vegetasi Hutan Mangrove untuk Mitigasi Intrusi Air Laut di Pulau Kecil. Oseanologi dan Limnologi di Indonesia, 5(2): 75-91 **(17 pages).**

Danielsen, F.; Sorensen, M.K.; Olwig, M.F.; Selvam, V.; Parish, F.; Burgess, N.D.; Quarto, A., (2005). The Asian tsunami: A protective role for coastal vegetation. Science, 310(5748): 643 **(15 pages).**

Das, S.; Crepin, A.S., (2013). Mangroves can provide protection against wind and swell waves. Estuarine Coastal Shelf Sci., 134: 98–107 **(14 pages).**

Dharmawan, I.W.E.; Pramudji., (2017). Panduan Pemantauan Komunitas Mangrove. Edisi 2. Coral Reef Rehabilitation and Management Program (COREMAP). Pusat Penelitian Oseanografi LIPI, 1-70 **(70 pages).**

Ding, Z.; Koriem, M.A.; Ibrahim, S.M.; Antar, A.S.; Ewis, M.A.; He, Z.; Kheir, A., (2020). Seawater intrusion impacts on groundwater and soil quality in the northern part of the Nile Delta, Egypt. Environ. Earth Sci., 79(13): 1-11 **(11 pages).**

Duke, N.C.; Meynecke, J.O.; Dittmann, S.; Ellison, A.M.;

Anger, K.; Berger, U. Dahdouh-Guebas, F., (2007). A world without mangroves? Science. 317(5834): 41-42 **(2 pages).**

Ellison, D.; Morris, C.E.; Locatelli, B.; Sheil, D.; Cohen, J.; Murdiyarso, D.; Sullivan, C.A., (2017). Trees, forests and water: Cool insights for a hot world. Global Environ. Change., 43: 51-61 **(11 pages).**

Gemilang, W.A.; Rahmawan, G.A.; Wisha, U.J., (2017). Kualitas Perairan Teluk Ambon Dalam Berdasarkan Parameter Fisika Dan Kimia Pada Musim Peralihan I. EnviroScienteae, 13(1): 79-90 **(12 pages).**

Gheuens, J.; Nagabhatla, N.; Perera, E.D.P., (2019). Disaster-risk, water security challenges and strategies in Small Island Developing States (SIDS). Water, 11(4): 637 **(28 pages).**

Giri, C.; Ochieng, E.; Tieszen, L.L.; Zhu, Z.; Singh, A.; Loveland, T.; Duke, N., (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecol. Biogeogr., 20(1): 154-159 **(6 pages).**

Gohar, A.A.; Cashman, A.; Ward, F.A., (2018). Managing food and water security in Small Island States: New evidence from economic modelling of climate stressed groundwater resources. J. Hydrol., 569, 239-251 **(13 pages).**

Goldberg, L.; Lagomasino, D.; Thomas, N.; Fatoyinbo, T., (2020). Global declines in human-driven mangrove loss. Global Change Biol., 26(10): 5844-5855 **(12 pages).**

Green, E.P.; Clark, C D.; Mumby, P.J.; Edwards, A.J.; Ellis, A., (1998). Remote sensing techniques for mangrove mapping. Int. J. Remote Sens., 19(5): 935-956 **(22 pages).**

Hao, X.; Ball, B.C.; Culley, J.L.B.; Carter, M.R.; Parkin, G.W., (2008). Soil sampling and methods of Analysis. CRC Press. Taylor and Francis Group, 300: 743-759 **(17 pages).**

Hilmi, E.; Kusmana, C.; Suhendang, E.; Iskandar, I., (2017). Correlation analysis between seawater intrusion and mangrove greenbelt. Indonesian J. For. Res., 4(2): 151-168 **(18 pages).**

Horstman E.M.; Lundquist C.J.; Bryan K.R.; Bulmer R.H.; Mullarney J.C.; Stokes D.J., (2018). The dynamics of expanding mangroves in New Zealand. In coastal research library: Threats to mangrove forests: hazards, vulnerability, and management. Springer Int. Publishing, 1-32 **(32 pages).**

Indarto, J.; Kaneko, S.; Kawata, K., (2015). Do forest permit cause deforestation in Indonesia? Int. For. Rev., 17(2): 165-181 **(17 pages).**

Ketabchi, H.; Mahmoodzadeh, D.; Ataie-Ashtiani, B.; Simmons, C.T. (2016). Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. J. Hydrol., 535: 235-255 **(21 pages).**

KLHK, (2023). Peta Mangrove Nasional Tahun 2023. Keputusan Menteri Lingkungan Hidup dan Kehutanan Nomor 6636 Tahun 2024. Kementrian Lingkungan Hidup dan Kehutanan **(7 pages).**

Krauss, K.W.; Lovelock, C.E.; McKee, K.L.; López-Hoffman, L.; Ewe, S.M.; Sousa, W.P., (2008). Environmental drivers in mangrove establishment and early development: A review. Aquat. Bot., 89(2): 105-127 **(17 pages).**

Kura, N.U.; Ramli, M.F.; Ibrahim, S.; Sulaiman, W.N.A.; Aris, A.Z.; Tanko, A.I.; Zaudi, M.A., (2015). Assessment of groundwater vulnerability to anthropogenic pollution and seawater intrusion in a small tropical island using index-based methods. Environ. Sci. Pollut. Res., 22(2): 1512-1533 **(22 pages).**

Lagomasino, D.; Price, R.M.; Whitman, D.; Campbell, P.K.; Melesse, A., (2014). Estimating major ion and nutrient concentrations in mangrove estuaries in Everglades National Park using leaf and satellite reflectance. Remote Sens. Environ., 154: 202-218 **(17 pages).**

Lee, S.Y.; Primavera, J.H.; Dahdouh-Guebas, F.; McKee, K.; Bosire, J.O.; Cannicci, S.; Record, S., (2014). Ecological role and services of tropical mangrove ecosystems: A reassessment. Global Ecol. Biogeogr., 23(7): 726–743 **(18 pages).**

Lukman, K.M., (2021). Blue carbon perceptions by locals deriving from coastal ecosystem services: A proposal for sustainable community-based managements in Indonesia. Doctoral dissertation, Tohoku University, 1-145 **(145 pages).**

Manson, F.; Loneragan, N.; Phinn, S., (2003). Spatial and temporal variation in distribution of mangroves in Moreton Bay, subtropical Australia: a comparison of pattern metrics and change detection analyses based on aerial photographs. Estuarine Coastal Shelf Sci., 57(4): 653-666 **(14 pages).**

McGarigal, K.; Cushman, S.; Ene, E., (2012). FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst, 15: 153-162 **(10 pages).**

Mello, K.; Valente, R.A.; Randhir, T.O.; Vettorazzi, C.A., (2018). Impacts of tropical forest cover on water quality in agricultural watersheds in southeastern Brazil. Ecol. Indic., 93: 1293-1301 **(9 pages).**

Meyer, S.; Kling, C.; Vogel, S.; Schröter, I.; Nagel, A.; Kramer, E.; Ruehlmann, J., (2019). Creating soil texture maps for precision liming using electrical resistivity and gamma ray mapping. In Precision agriculture, 19: 539-546 **(8 pages)**.

Murdiyarso, D.; Purbopuspito, J.; Kauffman, J.B.; Warren, M.W.; Sasmito, S.D.; Donato, D.C.; Kurnianto, S., (2015). The potential of Indonesian mangrove forests for global climate change mitigation. Nat. Clim. Change., 5(12): 1089-1092 **(4 pages).**

Nguyen, T.T.; Tran, D.Q.; Amano, A.; Hamaoka, H.; Tanabe, S.; Mai, T.N.; Omori, K., (2012). Historical profiles of trace element concentrations in mangrove sediments from the Ba Lat Estuary, Red River, Vietnam. Water Air Soil Pollut., 223: 1315–1330 **(16 pages).**

Noor, R.Y.; Khazali, M.; Suryadiputra, I.N.N., (2006). Panduan pengenalan mangrove di Indonesia. PHKA/WI-IP, Bogor Indonesia, 1 -10 **(10 pages).**

Ondara, K.; Rahmawan, G.A.; Wisha, U.J., (2017). Karakteristik hidrodinamika di perairan Teluk Ambon untuk mendukung

wisata selam. Indonesian J. Mar. Sci. Technol., 10(1): 67-77 **(11 pages).**

Patro, S.; Sahu, K.K., (2015). Normalization: A preprocessing stage. Int. Adv. Res. J. Sci. Eng. Technol., 2(3): 20-22 **(3 pages).**

Pires, A.P.; Rezende, C.L.; Assad, E.D.; Loyola, R.; Scarano, F.R., (2017). Forest restoration can increase the Rio Doce watershed resilience. Perspect. Ecol. Conserv., 15(3): 187-193 **(7 pages).**

Riitters, K.; Wickham, J.; O'Neill, R.; Jones, B.; Smith, E., (2000). Global-scale patterns of forest fragmentation. Conserv. Ecol., 4(2): 1-24 **(24 pages).**

Rotua, P.J. (2017). Kajian vegetasi mangrove di Teluk Ambon Dalam dengan menggunakan teknik penginderaan jarak jauh. Skripsi Program Studi Manajemen Sumberdaya Perairan, Universitas Pattimura, 1-68 **(68 pages).**

Saad, S.; Nawawi, M.N.M.; Muhamad, E.T., (2012). Groundwater detection in alluvium using 2-DeElectrical resistivity tomography (ERT). Electron. J. Geotech. Eng., 17(2): 369-376 **(8 pages).**

Santos, I.R.; Bryan, K.R.; Pilditch, C.A.; Tait, D.R., (2014). Influence of porewater exchange on nutrient dynamics in two New Zealand estuarine intertidal flats. Mar. Chem., 167: 57-70 **(14 pages).**

Schreiber, J.B.; Nora, A.; Stage, F.K.; Barlow, E.A.; King, J., (2006). Reporting structural equation modeling and confirmatory factor analysis results: A review. J. Educ. Res., 99(6): 323-338 **(16 pages).**

Setiawan, A.; Agustiadi, T.; Abida, R.F.; Theoyana, T.A.; Annisaa, M.; Ryandhini, N.A.; Sukadana, G.P.; Mahdalena, N.C.; Fadli, M.; Nurliansyah, W.; Kusmanto, E.; Asnaryanti, E., (2016). Laporan Ekspedisi Oseanografi Indonesia Bagian Timur Leg ke-3, Pusat Penelitian dan Pengembangan Sumberdaya Laut dan Pesisir. Kementerian Kelautan dan Perikanan, 1-74 **(74 pages).**

Shang, Y.; Lu, S.; Shang, L.; Li, X.; Wei, Y.; Lei, X.; Wang, H., (2016). Decomposition methods for analyzing changes of industrial water use. J. Hydrol., 543: 808-817 **(10 pages).**

Spalding, M.; Kainuma, M.; Collins, L., (2010). World atlas of mangroves. Routledge, 1-336 **(336 pages)**.

Suyadi, (2009). The Condition of Mangrove Forest in Ambon Bay: Prospect and Challenges. Berita Biologi, 9(5): 481 – 490 **(10 pages).**

Suyadi, Gao, J.; Lundquist, C.J.; Schwendenmann, L., (2018a). Characterizing landscape patterns in changing mangrove ecosystems at high latitudes using spatial metrics. Estuarine Coastal Shelf Sci., 215: 1-10 **(10 pages).**

Suyadi, Gao, J.; Lundquist, C.J.; Schwendenmann, L., (2018b). Sources of uncertainty in mapping temperate mangroves and their minimization using innovative methods. Int. J. Remote Sens., 39(1): 17-36 **(20 pages).**

Tamrin, Maricar, F.; Hatta, M.P.; Arsyad, A., (2021). Factors of causing seawater intrusion in Kadatua Island, Southeast Sulawesi. In IOP Conference Series: Earth Environ. Sci., 841(1): 012024 **(7 pages).**

Tatas, Budipriyanto, A.; Khoiri, M.; Lestari, W.; Rahman, A., (2015). Study on water balance in Poteran–a small island in East Java, Indonesia. Procedia Eng., 125: 236-242 **(7 pages).**

Thomas, N.; Lucas, R.; Bunting, P.; Hardy, A.; Rosenqvist, A.; Simard, M., (2017). Distribution and drivers of global mangrove forest change, 1996–2010. PloS One, 12(6): e0179302 **(14 pages).**

Tjokrosapoetro S.; Rusmana, E.; Acdan, A., (1993). Peta Geologi Ambon, Maluku. Pusat Penelitian Dan Pengembangan Geologi (P3G), Bandung, Indonesia, 2612–2613 **(2 pages).**

Uyara, L.; Kunu, P.; Talakua, S.M., (2017). Studi perbandingan kualitas air bersih dalam kaitanya dengan aktivitas masyarakat di sekitar sumber air pada Desa Wainitu, Batumerah, Amahusu, dan Halong. J. Budidaya Pertanian, 13(2): 111-119 **(9 pages).**

Vann, S.; Puttiwongrak, A.; Suteerasak, T.; Koedsin, W., (2020). Delineation of seawater intrusion using geo-electrical survey in a coastal aquifer of Kamala Beach, Phuket, Thailand. Water, 12(2): 506 **(14 pages).**

Vaz, E., (2014). Managing urban coastal areas through landscape metrics: An assessment of Mumbai's mangrove system. Ocean Coastal Manage., 98: 27-37 **(11 pages).**

Wendroth, O.; Koszinski, S.; Pena-Yewtukhiv, E., (2006). Spatial association among soil hydraulic properties, soil texture, and geoelectrical resistivity. Vadose Zone J., 5(1): 341-355 **(15 pages).**

Weston, N.B.; Vile, M.A.; Neubauer, S.C.; Velinsky, D.J., (2011). Accelerated microbial organic matter mineralization following salt-water intrusion into tidal freshwater marsh soils. Biogeochemistry, 102(1): 135-151 **(17 pages).**

Xiao, K.; Li, H.; Shananan, M.; Zhang, X.; Wang, X.; Zhang, Y.; Liu, H., (2019). Coastal water quality assessment and groundwater transport in a subtropical mangrove swamp in Daya Bay, China. Sci. Total Environ., 646: 1419-1432 **(14 pages).**

Xiao, K.; Wu, J.; Li, H.; Hong, Y.; Wilson, A.M.; Jiao, J.J.; Shananan, M., (2018). Nitrogen fate in a subtropical mangrove swamp: potential association with seawater-groundwater exchange. Sci. Total Environ., 635: 586-597 **(12 pages).**

Xiong, Y.; Liao, B.; Proffitt, E.; Guan, W.; Sun, Y.; Wang, F.; Liu, X., (2018). Soil carbon storage in mangroves is primarily controlled by soil properties: A study at Dongzhai Bay, China. Sci. Total Environ., 619: 1226-1235 **(10 pages).**

Zhang, K.; Liu, H.; Li, Y.; Xu, H.; Shen, J.; Rhome, J.; Smith III, T.J., (2012). The role of mangroves in attenuating storm surges. Estuarine Coastal Shelf Sci., 102: 11–23 **(13 pages).**

AUTHOR (S) BIOSKETCHES

Suyadi, Ph.D., Principal Scientist, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Bogor Indonesia.
- Email: *pedhetsuyadi@gmail.com* and *suya010@brin.go.id*
- ORCID: 0000-0001-7476-7130
- Web of Science ResearcherID: MBV-0795-2025
- Scopus Author ID: 57202031356
- Homepage: https://www.brin.go.id/

Basyuni, M. Ph.D., Professor, Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *m.basyuni@usu..ac.id*
- ORCID: 0000-0003-1120-8571
- Web of Science ResearcherID: D-8537-2015
- Scopus Author ID: 15055287200
- Homepage: https://puimangroveusu.id/

Amukti, R. Ph.D. Candidate and Researcher, Research Center for Geological Disaster, National Research and Innovation Agency (BRIN), Bandung, Indonesia..
- Email: *rian.amukti87@gmail.com*
- ORCID: 0000-0003-0949-306X
- Web of Science ResearcherID: NA
- Scopus Author ID: 57213194117
- Homepage: https://www.brin.go.id/

Damayanti, C. Ph.D. Candidate and Researcher, Research Center for Geological Disaster, National Research and Innovation Agency (BRIN), Bandung, Indonesia.
- Email: *cakra.cahya@gmail.com*
- ORCID: 0009-0007-7514-8623
- Web of Science ResearcherID: NA
- Scopus Author ID: 5837016840
- Homepage: https://www.brin.go.id/

Stokers, D. Ph.D., Associate Professor, Faculty of Science and Engineering, Southern Cross University, Australia.
- Email: *debra.stokes@scu.edu.au*
- ORCID: 0000-0003-1353-9438
- Web of Science ResearcherID: NA
- Scopus Author ID: 26649016900
- Homepage: https://www.scu.edu.au/

Mubaraq, A., M.Agr., Ph.D Candidate, Graduate School of Agricultural Science, Faculty of Agriculture, Universitas Sumatera Utara, Medan 20155, Indonesia
- Email: *alfian@students.usu.ac.id*
- ORCID: 0009-0005-9810-3896
- Web of Science ResearcherID: JTU-5714-2023
- Scopus Author ID: 59122664800
- Homepage: https://www.usu.ac.id/

Rahmila, Y.I. Ph.D. Candidate and Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Bandung, Indonesia.
- Email: mila.yulizar@gmail.com
- ORCID: 0000-0002-7253-4787
- Web of Science ResearcherID: NA
- Scopus Author ID: 57205344845
- Homepage: https://www.brin.go.id/

HOW TO CITE THIS ARTICLE

Suyadi; Basyuni, M.; Amukti, R.; Damayanti, C.; Stokes, D.; Mubaraq, A.; Rahmila, Y.I., (2025). Ecological features of mangroves as indicators of seawater intrusion. Global J. Environ. Sci. Manage., 11(2): 609-630.

DOI: 10.22034/gjesm.2025.02.14

URL: https://www.gjesm.net/article_720632.html

Global J. Environ. Sci. Manage. 11(2): 631-652, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Ecological population dynamics, host preferences, and associated parasitoids of *Bactrocera carambolae* and *Bactrocera papayae* on fruits

D. Koswanudin[1], H.Widyanto[1], D. Hutapea[2,*], Wawan[1], R. Yuniawati[1], V.N.O. Subagyo[1], S. Utami[1], I.M. Samudra[1], W. Darwiati[1]

[1] *Research Center for Applied Zoology, National Research and Innovation Agency, Cibinong-Bogor, West Java, Indonesia*

[2] *Research Center for Horticulture Crops, National Research and Innovation Agency, Cibinong-Bogor, West Java, Indonesia*

ARTICLE INFO

Article History:
Received 09 November 2024
Revised 13 January 2025
Accepted 18 February 2025

Keywords:
Attractant
Monitoring
Population dynamics
Surveillance
Tephritidae

ABSTRACT

BACKGROUND AND OBJECTIVES: Fruit flies are a significant pest affecting fruit production in Indonesia. Understanding the species of fruit flies in fruit-growing regions is crucial for evaluating pest risk, establishing effective plant quarantine measures, and managing control programs. This study aimed to analyze the population dynamics and host preferences of *Bactrocera carambolae* and *Bactrocera papayae* on multiple fruit plants, in addition to exploring the parasitoids associated with these two species of fruit flies.

METHODS: The study was conducted using a survey method in Bogor, Depok, and Indramayu Regency fruit gardens by installing methyl eugenol traps. Randomly selected infected fruits were collected and brought to the laboratory in cages, where they were kept until the emergence of the fruit flies.

FINDINGS: The results show that *Bactrocera carambolae* was more abundant than Bactrocera papayae captured in methyl eugenol-baited traps, particularly during the rainy season. *Bactrocera carambolae* favored star fruit as a host (907.79 flies/trap/month), while Bactrocera papaya preferred papaya (208.46 flies/trap/month), highlighting their distinct oviposition behaviors. The average catches indicated that *Bactrocera carambolae* thrived in moist conditions, while *Bactrocera papayae* flourished in warmer temperatures. Four parasitoid species were identified, including Diachasmimorpha longicaudata and Fopius arisanus, with parasitization rates of 20.40 percent and 12.70 percent, respectively. The findings underscore the potential for effective biological control of the targeted pest species. They indicate that seasonal variations in the availability of host fruits and climatic conditions play a significant role in influencing fruit fly populations and their relationships with parasitoids.

CONCLUSION: This study emphasizes the population dynamics and host plant preferences of *Bactrocera carambolae* and *Bactrocera papayae* in West Java, Indonesia. Four parasitoid species were identified, with Diachasmimorpha longicaudata and Fopius arisanus showing high parasitism rates, suggesting their potential to control fruit fly populations. This study underscores the significance of climate conditions and host availability in creating sustainable and effective pest management approaches for the fruit industries in Indonesia.

DOI: 10.22034/gjesm.2025.02.15

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
54	9	3

*Corresponding Author:
Email: *dedi026@brin.go.id*
Phone: +62-81396614662
ORCID: 0000-0002-1801-1918

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

The agricultural sector plays a crucial role in Indonesia's development, particularly in managing and utilizing strategic resources and food commodities. Within its diverse sub-sectors, horticulture is notable for its substantial potential and its role in enhancing farmers' welfare, driving regional and national economic growth, and generating foreign exchange through export activities. In 2022, the horticulture sector accounted for 1.44 percent (%) of Indonesia's gross domestic product (GDP) (CSAI, 2024a). In 2023, the value of fruit exports will increase by 9.8% compared to 2022. In 2023, the expected revenue from fruit exports is anticipated to reach 460 thousand United States Dollars (USD) (CSAI, 2024b). West Java Province is one of Indonesia's major fruit-producing regions. Several horticultural commodities widely cultivated in West Java and other parts of Indonesia include mango (*Mangifera indica*), star fruit (*Averrhoa carambola*), guava (*Psidium guajava*), Malay apple (*Syzygium malaccense*), and water apple (*Syzygium aqueum*). Rich in vitamins, these fruits are often utilized in beverage formulations and provide various health benefits, including the ability to lower blood pressure and satisfy nutritional demands (Haryono *et al.,* 2016; Yuliadhi *et al.,* 2022; Setiawan *et al.,* 2024). Due to their high economic value, fruit production has steadily increased. In 2023, mango, star fruit, guava, Malay apple, and water apple contributed significantly to the total fruit production in West Java, accounting for 13.6%, 11.6%, 7.3%, 16.9%, and 14.24%, respectively (CSAI, 2024 b). A key factor hindering fruit production is the risk posed by fruit fly infestations. These insects are notable pests of fruit crops and are regarded as primary plant pest organisms. These pests are categorized as quarantine threats, posing significant challenges to the global fruit trade. Infestations found in exported fruits may result in rejection by importing countries, thereby hindering agribusiness operations (Fitrah *et al.,* 2021; Susanto *et al.,* 2022). Fruit flies cause both quantitative and qualitative losses. Quantitative losses arise from diminished harvestable yields, whereas qualitative losses impact the quality of the fruit, especially when secondary bacterial infections lead to fruit decay. Additionally, fruit fly larvae damage the fruit flesh, leading to premature decay and fruit drop before reaching maturity (Danjuma *et al.,* 2014; Muryati *et al.,* 2017). A comprehensive survey has identified 29 different species of fruit flies present throughout the islands of Indonesia (Hidayat *et al.,* 2023). Ardiyanti et al. (2019) reported the presence of 18 fruit fly species in the Bogor area and its surroundings. *Bactrocera* spp. (Diptera: Tephritidae) are among the most significant pests of horticultural crops worldwide, with more than a hundred horticultural plant species serving as potential hosts. In high population densities, infestation intensity can reach up to 100%. Several *Bactrocera* species, including *Bactrocera dorsalis, Fopius arisanus, Bactrocera papayae,* and *Bactrocera philippinensis*, pose serious threats to international agriculture and trade (Ardiyanti *et al.,* 2019; Hidayat *et al.,* 2023; Setiawan *et al.,* 2024). The species *B. carambolae* and *B. papayae* are major concerns for tropical fruit production in Indonesia, leading to considerable repercussions for local and export markets. Infested fruit can lead to trade restrictions and rejections from importing countries (Haryono *et al.,* 2016; Sudiarta *et al.,* 2020; Putri *et al.,* 2024). Consistently recognized as key pests, these two species pose a serious threat to numerous fruits and vegetables in Indonesia, emphasizing the pressing requirement for efficient pest control strategies (Danjuma *et al.,* 2014; Susanto *et al.,* 2022; Putri *et al.,* 2024). Various technologies have been developed for fruit fly control, including fruit bagging, releasing sterile male insects, traps with methyl eugenol, and applying chemical pesticides (Danjuma *et al.,* 2014; Theron et al., 2017; Setiawan *et al.,* 2024). Utilizing natural predators like parasitoid wasps has surfaced as an effective strategy in the realm of sustainable pest management (Vargas *et al.,* 2013; Miranda *et al.,* 2015). Biological control is particularly advantageous as it eliminates chemical residues in fruits, enhances environmental safety, and reduces the risk of pollution (Hudiwaku *et al.,* 2021; Dias *et al.,* 2022). The larval parasitoid from the Braconidae family may serve as a natural enemy to fruit flies (Vargas *et al.,* 2013; Miranda *et al.,* 2015). The Braconidae family, the second-largest family after Ichneumonidae within the Hymenoptera order, primarily consists of parasitoid members (Ovruski *et al.,* 2009). These parasitoids demonstrate a wide host range, preying on a variety of insect pests, including lepidopteran larvae, scale insects, and fruit fly larvae (Vargas *et al.,* 2013; Miranda *et al.,* 2015). Indonesia has documented instances of various parasitoids from the Braconidae family engaging

fruit flies, notably *Fopius arisanus*, *Diachasmimorpha longicaudata*, *F. vandenboschi*, *Opius* sp., and *Biosteres* sp. (Haryono *et al.,* 2016; Ardiyanti *et al.,* 2019). Of particular interest, *D. longicaudata* and *F. arisanus* have emerged as promising agents in Indonesia's biological control of fruit fly populations (Haryono *et al.,* 2016; Hudiwaku *et al.,* 2021). To develop successful strategies for managing fruit flies, it is crucial to have an in-depth understanding of the pest species involved (Dias *et al.,* 2022; Yuliadhi *et al.,* 2022; Dominiak and Follett, 2024). The understanding of *B. carambolae* and *B. papayae* species, particularly their population dynamics, host preferences, and associated parasitoids, remains limited. The objective of this study is to investigate the population dynamics and host selection of *Bactrocera carambolae* and *Bactrocera papayae* on multiple fruit plants, in addition to exploring the parasitoids associated with these two two fruit fly species. This study was carried out at Indonesian Center for Agricultural Biotechnology and Genetic Resources Instrument Standard Testing, Bogor, West Java, Indonesia, in 2021.

MATERIALS AND METHODS

Location and sampling sites studied

The research is divided into two parts: field exploration and laboratory experiments. The field research was conducted in the fruit orchard area of Mekarsari Fruit Garden, Cileungsi District, Bogor Regency (S 06°22'401' E 106°58.951'), farmer orchards in Pancoran Mas District, Depok (S 06°22'293', E 106°53'924'), and farmer orchards in Krasak Village, Jatibarang District, Indramayu Regency (S 06°27'40.42" S, E 108°17'55.29"), West Java Province, Indonesia (Fig. 1). In West Java Province, these three areas are vital production hubs for star fruit, mango, guava, papaya, and water apple, overseen by small and medium-scale farmers and entrepreneurs. The study took place at the Entomology Laboratory within the Indonesian Center for Agricultural Biotechnology and Genetic Resources Instrument Standard Testing, Bogor. This research focused on two species of fruit flies, *Bactrocera carambolae* and *Bactrocera papayae*. In Indonesia, these pests represent a serious challenge, leading to substantial economic losses in the cultivation of fruits and vegetables. The polyphagous insect of these two fruit fly species poses a serious threat to commercial crops, including vegetables and fruits such as mango, star fruit, water apple, guava, malay apple, papaya, melon, breadfruit, jackfruit, tomato, and chili. Field exploration was conducted to assess the population dynamics of fruit flies in traps and infested fruits, as



Fig. 1: Geographical location of the study area in west Java Province, of Indonesia indicated with green, red, and yellow circles indicating the trapping locations of fruit flies

well as their associated parasitoids. Meanwhile, the laboratory research aimed to evaluate the preference and performance of fruit flies on several host plants. The host plants used in this research consisted of five types: star fruit (*Averrhoa carambola*), mango (*Mangifera indica*), guava (*Psidium guajava*), water apple (*Syzygium aqueum*), and papaya (*Carica papaya*).

Population dynamics of fruit flies

The population dynamics of *B. carambolae* and *B. papayae* fruit flies were monitored using two methods: installing attractant traps containing methyl eugenol and collecting infested fruits. This section of the study yielded important findings regarding the population dynamics of fruit flies in relation to various host plants and the fruits impacted by infestations in agricultural areas focused on fruit production.

Fruit flies in traps

The traps used in this study were Steiner traps modified from Hasyim *et al.* (2008). These traps made from plastic bottles, each 30 centimeters (cm) in length and 8 cm in diameter. A pair of holes, each 1 cm in diameter, was drilled on opposite sides of the bottle, permitting the insertion of a tube for fruit fly access. A wire was attached to the bottle's cap to suspend the tube, which was 0.3 cm in diameter and 2 cm in length, containing methyl eugenol-soaked cotton, which was positioned in the upper third of the bottle. At the bottom, 4 cm of liquid detergent diluted with water was added as a killing agent for captured fruit flies. The traps were installed on five host plants: star fruit, mango, guava, water apple, and papaya. They were placed 1,5 meters above ground level beneath the tree canopy (Hasyim *et al.,* 2006). Four traps were installed in each location, covering an area of approximately 5000 square meters (m^2), spaced 20 meters apart. The observation period spanned 12 months, with sessions held at three-day intervals. The total number of fruit fly species captured in all traps was recorded and identified based on Siwi *et al.* (2006).

Fruit flies within fruits infested

Infested fruits were collected from star fruit, mango, guava, water apple, and papaya. Over the course of the study, collections were performed 12 times at two-week intervals, with ten fruit samples from each species collected during each session. They were kept at 28 degrees Celsius (°C) and 70% relative humidity. The fruits were stored in plastic jars measuring 6 cm in diameter and 20 cm in height with nylon mesh covering the top. After a 14-day incubation, the fruit was peeled to obtain the pupae of the fruit flies. Each pupa was transferred to a plastic box measuring 10 cm × 10 cm × 5 cm, with the bottom lined with sterile sawdust. The development of the pupae was monitored on a daily basis until the adult fruit flies emerged, after which the species were identified and the number of individuals was counted.

Mass rearing of fruit flies

Fruit flies were obtained from infested fruits collected from the Mekarsari Fruit Garden. Identification of the fruit flies was conducted to select the appropriate species for the study, namely *B. carambolae* and *B. papayae*. The mass rearing of both species was carried out in the laboratory under temperature of 28 °C, humidity of 70%, and 12 hours (h) lighting. The infested fruits were kept in cages measuring 50 cm × 50 cm × 25 cm, with a six cm-thick layer of sawdust at the base to serve as a pupation site. Weekly sifting of the sawdust was conducted to extract and collect the pupae that had formed. All collected pupae were stored in petri dishes and placed in cages measuring 40 cm × 40 cm × 40 cm. Inside these cages, adult fruit flies were provided with food consisting of sponges soaked in water, petri dishes containing a mixture of protein hydrolysate and granulated sugar (1:4, weight per weight (w/w)), and honey solution (10%) soaked in cotton (Vargas *et al.,* 2000; Hasyim *et al.,* 2008). Following a ten-day interval, eggs were harvested with a tube that measured 1.5 cm in diameter and 15 cm in height, and they were preserved until they reached the pupal stage. Pupae that had formed within the sawdust were collected by passing the material through a 60-mesh screen, and the adult fruit flies that emerged were subsequently returned to cages for further cultivation.

Host preference of B. carambolae and B. papayae on different fruits

Five hundred pairs of male and female *B. carambolae* and *B. papayae* were placed separately in cages measuring 50 cm × 50 cm × 50 cm, with methyl eugenol applied to stimulate copulation.

After copulation, 100 females were replaced with plastic containers measuring 30 cm in height and 30 cm in diameter connected to five smaller containers measuring 17 cm in height and 16 cm in diameter. Host fruit designated for oviposition was placed in each of the smaller containers. An exhaust fan was installed at the upper section of the fruit fly enclosure to direct the scent of the fruit into the containers, facilitating the entry of fruit flies into the container that corresponded to their preferred host fruit. Fruit fly infestation on the host fruits was recorded over 48 h, after which all females were removed from the plastic containers. Utilizing jars to confine fruit flies in order to study host preference may not completely mimic their natural conditions, which points to a limitation within this study. The experiment was conducted using a completely randomized design with five treatments (star fruit, papaya, guava, water apple, and papaya) and four replications. The host preference tests for *B. carambolae* and *B. papayae* were conducted separately for each species at different times. The study monitored several parameters, including the number of fruit flies that approached the host fruit, the total oviposition punctures made, the number of eggs laid, the count of pupae, the duration of the pupal phase, the number of adult fruit flies that emerged, the emergence rate of pupae into adults, and the sex ratio of the adults.

Fruit fly parasitoids

The observation of parasitoids was carried out by collecting infested fruits. The study focused on star fruit, mango, and guava, with a total sample of 50 infested fruits collected from each host species. All harvested fruits were stored in plastic containers, each measuring 20 cm in height and 15 cm in diameter, with a layer of sterilized sawdust at the bottom to facilitate pupation. The infested fruits were incubated for 14 days before being peeled to extract the fruit fly pupae until 100 pupae for each host fruit. Each pupa was replaced with a plastic container measuring 10 cm × 10 cm × 5 cm, with sterilized sawdust lining the bottom. The development of pupae was monitored on a daily basis to identify the emergence of either fruit flies or parasitoids. Parasitoids were identified using the identification keys by Goulet and Huber (1993) and Shaw and Huddleston (1991).

Data analysis

The data on the population dynamics of fruit flies were analyzed using analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test at a 5% significance level. Data on abiotic factors such as temperature, rainfall, and rainy days were sourced from climate stations in Bogor, Indramayu, and Depok, West Java Province, and subsequently averaged on a monthly basis. Further examination of the data was carried out utilizing Pearson correlation and generalized linear model (GLM) regression analysis. The analyses were executed withR version 4.1.1.

RESULTS AND DISCUSSION

Fruit flies caught in traps

Two species of adult male fruit flies were captured in methyl eugenol-baited traps during the study. Based on morphological characteristics, the two fruit flies were identified as *Bactrocera carambolae* Drew and Hancock and *Bactrocera papayae* Drew and Hancock. The main morphological feature of *B. carambolae* is the overlapping of the costal band of the wing with vein R_{2+3}. The abdomen displays a T-shaped arrangement featuring a prominent dark band that runs longitudinally in the center, while the anterolateral corner of the fourth tergite is shaped like a square (Fig. 2B). In contrast, the main morphological feature of *B. papayae* is that the costal band of the wing runs parallel to or crosses R_{2+3}. The abdomen presents a T-shaped design featuring a narrowed dark band along the medial longitudinal axis, with the anterolateral corner of the fourth tergite appearing either triangular or not present at all (Fig. 3B). Both species of fruit flies are polyphagous pests with a wide host range, including star fruit, jackfruit, mango, papaya, citrus, water apple, guava, malay apple, soursop, sugar apple, avocado, chili peppers, cayenne pepper breadfruit, cempedak, and rambutan. The current study did not perform molecular analyses on the two fruit fly species, *B. carambolae* and *B. papayae*. Nevertheless, there is a wealth of research that has examined the genetic variations that exist between these species. Studies employing microsatellite markers have shown that there are notable genetic differences in B. carambolae populations depending on their geographic regions (Schutze *et al.,* 2014; Aketarawong *et al.,* 2015). These variations influence their adaptability and infestation patterns. *B. papayae* is more invasive, having successfully spread across Southeast Asia due to its

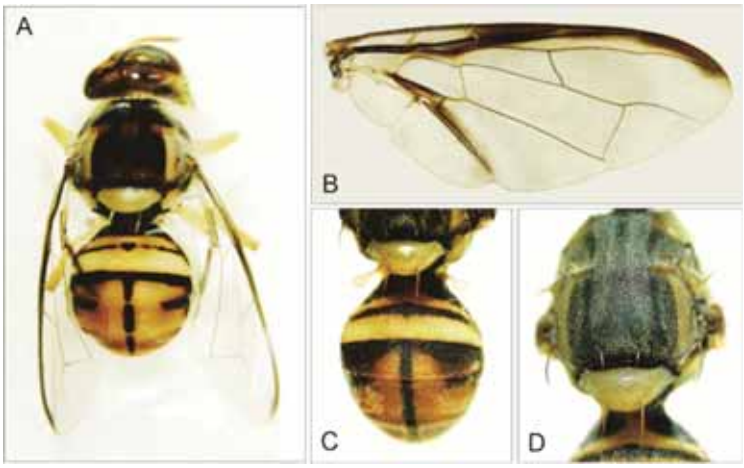


Fig. 2: *Bactrocera carambolae* male. A) dorsal view, B) wing, C) abdomen, D) scutum

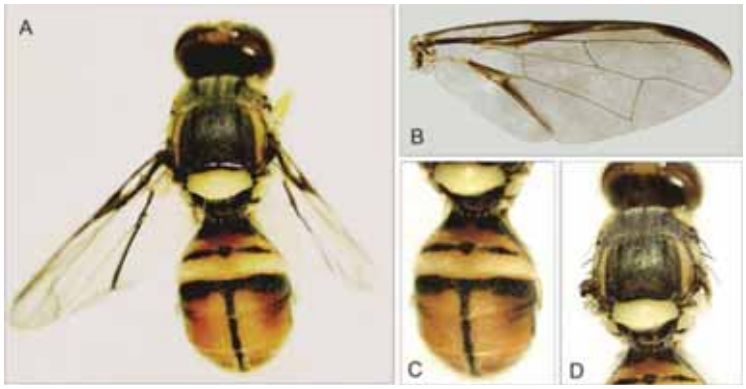


Fig. 3: *Bactrocera papayae* male. A) dorsal view, B) wing, C) abdomen, D) scutum

greater genetic diversity and adaptability to various host plants and climates (Qin *et al.,* 2018; Jaffar *et al.,* 2023). In contrast, *B. carambolae* remains largely confined to the northern regions of South America, where it primarily infests *Averrhoa carambola* (Deus *et al.,* 2024).

The population of both fruit fly species varied each month among the orchards. *B. carambolae* was captured significantly more than *B. papayae* across all observed fruit types and was most abundant during the rainy season. The presence of fruit flies in the traps was notably impacted by variations in rainfall and temperature (Fig. 4). The results of this study demonstrate that methyl eugenol is effective for monitoring male populations of *B. carambolae* and *B. papayae*. Adult *B. carambolae* catches were generally higher in February, March, October, November, and December, coinciding with increased rainfall (Fig. 4A). Conversely, the capture rates of male B. *papayae* appeared to increase with higher maximum temperatures and a reduction in rainfall (Fig. 4B). Indonesia is an equatorial country with a tropical climate characterized by warm temperatures and high humidity throughout the year. Indonesia experiences two seasons: the rainy season, which lasts from October to March, and the dry season, which typically occurs from April to September. Table 1 illustrates the correlation between the abundance of fruit flies and various weather parameters. Rainfall indicated a positive and significant correlation with the abundance of *B. carambolae*, whereas temperature did not show a significant correlation. In contrast, there was a positive correlation between maximum temperature and the abundance of *B.*

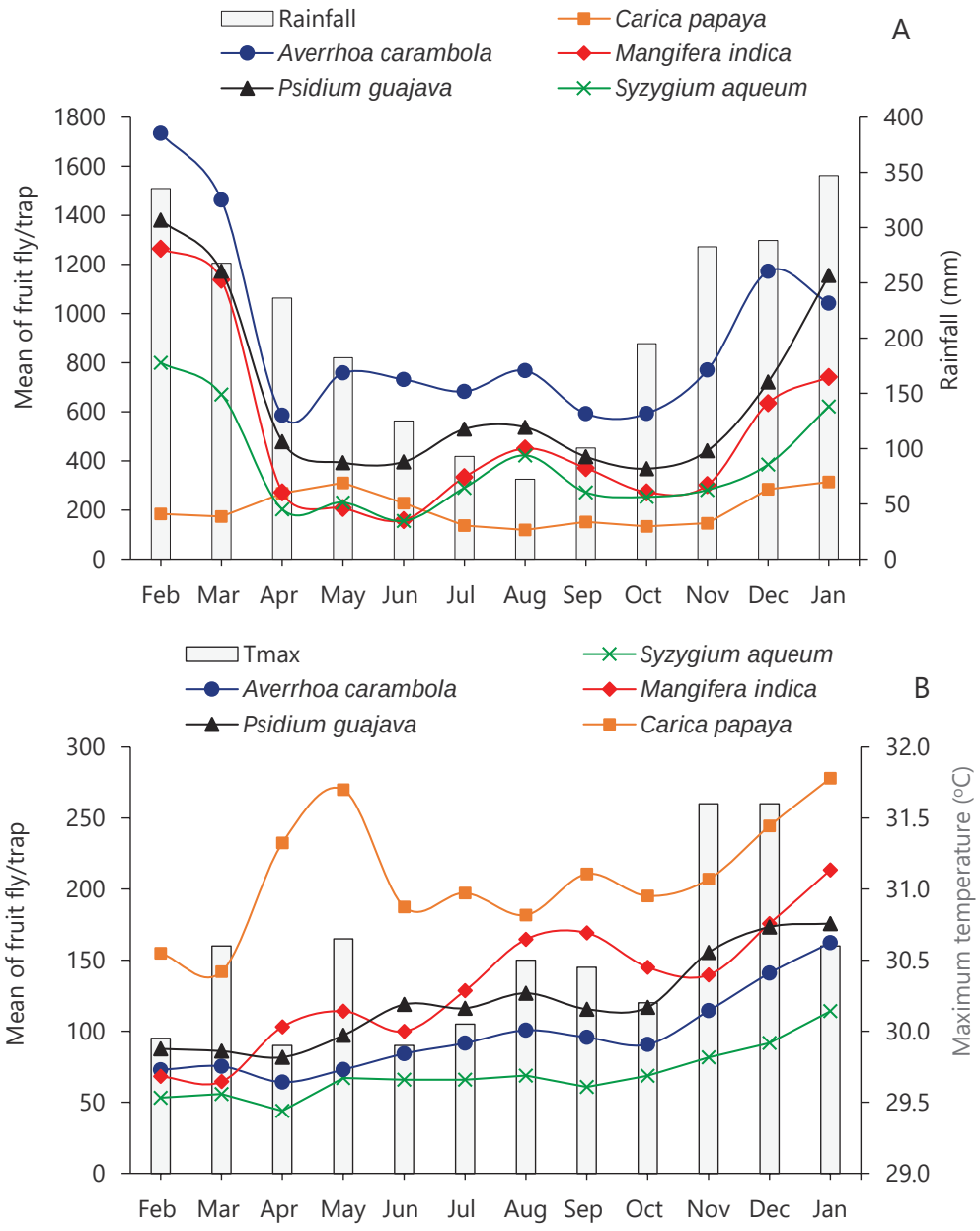


Fig. 4: Population dynamics of male fruit flies collected per trap per month in relation to rainfall and *B. carambolae* (A), and maximum temperature and *B. papayae* (B) in orchards of star fruit, mango, guava, water apple, and papaya

papayae on host plants, excluding mango, while rainfall did not reveal any significant correlation. Generally, weather factors, temperature, and rainfall were essential variables influencing the distribution of fruit flies. The variations in climate noted in this study imply potential consequences related to climate change. It is projected that climate change will impact fruit fly populations by extending their distribution, changing their life cycles, and increasing the likelihood of infestations. Rising temperatures and changing precipitation patterns may facilitate the spread of invasive species into new regions.

Table 1: Relations between weather parameters and male fruit flies caught per trap per month in orchards of star fruit, mango, guava, water apple, and papaya

Host plant	Pearson correlation coefficient (r)				Multiple linear regression equation (Y)	R^2
	X_1	X_2	X_3	X_4		
B. carambolae						
A.carambola	0.101	0.408	-0.022	0.628*	$Y= 5372 - 339 X_1 - 333 X_2 + 457 X_3 + 5.37 X_4$	51.81
M. indica	0.019	0.375	-0.135	0.588*	$Y= 8865 - 360 X_1 - 321 X_2 + 317 X_3 + 5.04 X_4$	46.95
P.guajava	-0.035	0.487	-0.239	0.671*	$Y= 10300 - 321 X_1 - 215 X_2 + 137 X_3 + 4.48 X_4$	56.00
C. papaya	0.130	0.481	0.388	0.681*	$Y= -3636 + 39.3 X_1 + 74.7 X_2 + 49.7 X_3 - 0.16 X_4$	61.99
S. aqueum	0.017	0.313	-0.281	0.575*	$Y= 7147 - 188 X_1 - 179 X_2 + 76 X_3 + 2.71 X_4$	46.76
B. papayae						
A.carambola	0.599*	-0.072	-0.301	0.308	$Y= -294 + 42.4 X_1 + 13.2 X_2 - 46.4 X_3 - 0.10 X_4$	53.96
M. indica	0.425	-0.272	-0.198	-0.072	$Y= -587 + 66.6 X_1 + 29.9 X_2 - 73.9 X_3 - 0.38 X_4$	43.86
P.guajava	0.676*	-0.215	-0.264	0.203	$Y= -422 + 51.0 X_1 + 11.2 X_2 - 49.1 X_3 - 0.13 X_4$	61.68
C. papaya	0.511*	0.302	0.211	0.179	$Y= -2135 + 65.5 X_1 + 63.5 X_2 - 32.3 X_3 - 0.45 X_4$	52.28
S. aqueum	0.573*	-0.006	-0.320	0.317	$Y= -257 + 31.2 X_1 + 14.9 X_2 - 36.3 X_3 - 0.11 X_4$	57.49

X_1 = maximum temperature; X_2= minimum temperature; X_3= average temperature, X_4= rainfall (mm); Y = number of fruit flies; * Significant at P≤0.05.

Evidence suggests that the ideal habitats for fruit flies are evolving, emphasizing the importance of implementing updated monitoring and management strategies. Furthermore, variations in temperature can influence the development and reproduction of fruit flies, thereby impacting their population dynamics (Jaffar *et al*., 2023; Kolopaking *et al.,* 2023). These findings emphasize the importance of adaptive pest control strategies to mitigate climate-related threats.

The present study revealed that the average abundance of male *B. carambolae* captured was highest on star fruit (907.79 flies/trap/month), followed by guava (666.23 flies/trap/month), mango (512.67 flies/trap/month), water apple (382.67 flies/trap/month), and papaya (204.41 flies/trap/month). The capture rate of male *B. carambolae* on star fruit was found to be statistically significantly greater, with the exception of comparisons made with guava (Fig. 5). Furthermore, male *B. papayae* were most frequently captured on papaya (208.46 flies/trap/month), with a statistically significant difference compared to mango (132.20 flies/trap/month), guava (120.97 flies/trap/month), star fruit (97.17 flies/trap/month), and water apple (69.75 flies/trap/month).

The current study reveals that *Bactrocera carambolae* and *Bactrocera papayae* were the two main species of fruit flies affecting fruit cultivation in Indonesia, particularly in West Java Province. Both species are polyphagous, capable of infesting over 300 host plants across 40 families (Amin *et al.,* 2019). The prevalence of fruit flies is influenced by factors such as geographic location, seasonal variations, the presence of specific host plants, and the fruiting period of host plants (Danjuma *et al.,* 2014; Amin *et al.,* 2019; Hudiwaku *et al.,* 2021). The success of pupation and emergence rates for *B. carambolae* and *B. papayae* are greatly affected by site conditions, including soil composition and the characteristics of microhabitats (Susanto *et al.,* 2022; Lin and Okuyama, 2024). Soil texture, moisture content, potential of hydrogen (pH), and pupation depth significanly influence the pupation success and emergence rates of these fruit flies. Sufficient soil moisture is essential for successful pupation. While there is limited research focused specifically on *B. carambolae* and *B. papayae*, studies on related species indicate that both excessively dry and overly moist soil conditions can adversely affect the survival and emergence of pupae (Susanto *et al.,* 2022; Lin and Okuyama, 2024). The present study indicates that *B. carambolae* was present in significantly higher abundance than *B. papayae*, with peak populations occurring during the rainy season. These findings align with Setiawan *et al*. (2024), who monitored fruit fly composition on several host plants (apple, large chili, red guava, sweet citrus, and tomato) and found that *B. carambolae* ranked first, while *B. papayae* ranked third in terms of captured fly populations. Likewise, Putri *et al*. (2024) conducted an assessment of fruit fly populations through the use of pheromone traps, revealing that male *B. carambolae* were more prevalent than other fruit fly species. They also reported that fruit fly populations peaked in October and March but declined until April and

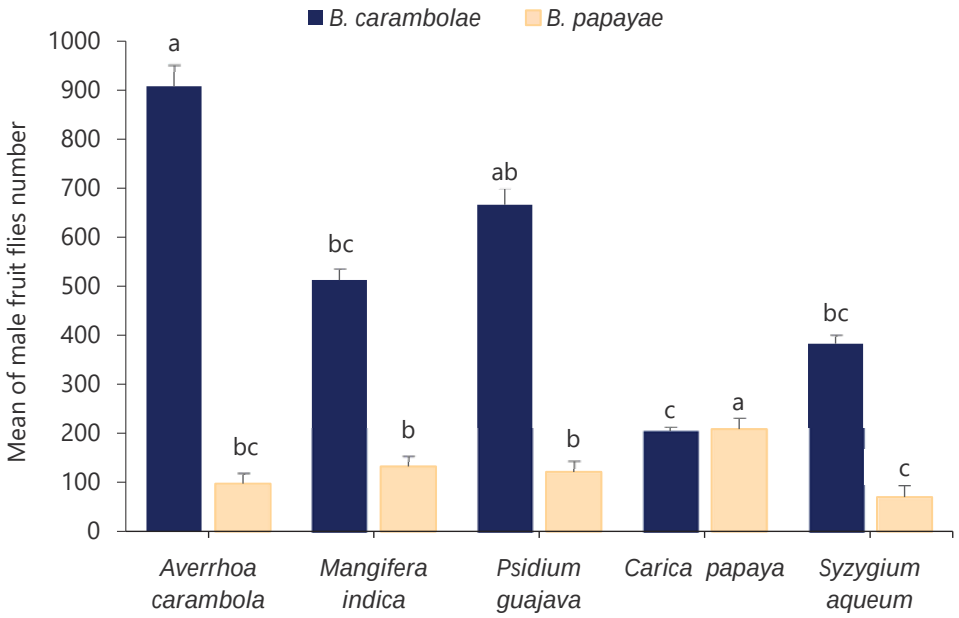


Fig. 5: The mean number of *B. carambolae* and *B. papayae* male caught per trap during a year in star fruit, mango, guava, water apple, and papaya orchards. Values are mean ± standard error (SE). The means with the same letters for each variable were not significantly different (Tukey's HSD, $P < 0.05$)

September. A combination of environmental factors and intrinsic characteristics of the species and individuals influences the dynamics of fruit fly populations. This study found a significant association between the number of trapped fruit flies and environmental conditions, particularly temperature and rainfall. It was indicated that increased temperature and rainfall enhance the number of fruit flies captured in traps. The study shows that rainfall, temperature, and host plant species are the primary environmental factors affecting the population fluctuations of *B. carambolae* and *B. papayae*. The dynamics of fruit fly populations in tropical regions are shaped by various essential elements, including the availability of host and non-host plants, along with temperature and precipitation levels (Danjuma *et al.,* 2014; Pogue *et al.,* 2024). The population of fruit flies directly influences the population of other insects, particularly their parasitoids. A rise in the population of fruit flies is associated with an increase in the number of parasitoids, whereas a reduction in fruit flies corresponds to a decrease in parasitoid numbers (Ardiyanti *et al.,* 2019; Susila and Supartha, 2020). Overall, the temperature conditions in West Java Province were suitable for the population development of *B. carambolae* and *B. papayae*, which explains why these fruit flies are present throughout the year. The air temperature during the dry season tends to be higher, falling within the optimal range for *B. papayae*, which favors an increase in its population. Additional findings suggest that sustained elevated temperatures benefit the population development of *B. papayae*. The monthly maximum temperatures at the study locations ranged from 29.90 °C to 31.60 °C, representing ideal conditions for insect development year-round. emperature is a key factor affecting the growth and survival of *B. papayae*, which demonstrates a greater adaptability to higher temperatures than *B. carambolae*. In general, *B. papayae* prospers in regions where the temperature is between 25 °C and 30 °C (Danjuma *et al.,* 2014; Amin *et al.,* 2019; Pogue *et al.,* 2024). Conversely, the high rainfall during the study period was beneficial for the population development of *B. carambolae*. The location where *B. carambolae* was discovered experienced an extended rainy season and recorded the highest density throughout this study. Weather data collected during the study revealed a distinct difference between the dry and

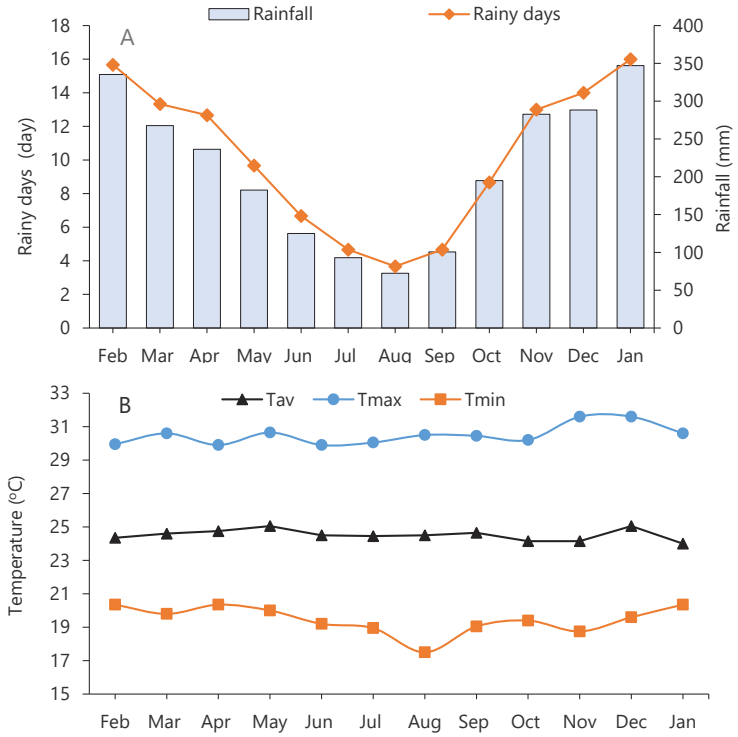


Fig. 6: Weather conditions at the research sites. Rainfall with rainy days (A) and monthly temperature (Tav: average temperature, Tmax: maximum temperature, Tmin: minimum temperature). The rainy season corresponds from October to March, while the dry season corresponds from April to September 2021

rainy seasons in terms of rainfall but not in temperature, with more significant precipitation occurring during the rainy season (Fig. 6). Susanto *et al.* (2017) and Putri *et al.* (2024) captured more fruit flies in traps during periods of rainfall between 160 and 200 millimeters (mm) (comparable to the rainfall levels in this study). Generally, fruit fly populations increase with rising rainfall (Hasyim *et al.*, 2008; Putri *et al.*, 2024). The survival, reproductive rates, and movement patterns of adult flies are directly influenced by rainfall, which also has an indirect effect on the availability of host fruits and the presence of natural enemies (Amin *et al.*, 2019). Increased rainfall can trigger the emergence of new adults; however, excessive rain can lead to pupal mortality and hinder the daily activity of fruit flies (Dominiak and Follett, 2024; Soares *et al.*, 2023). Furthermore, increased rainfall impacts the synchronization of growth and development in host plants (Hasyim *et al.*, 2008; Amin *et al.*, 2019). The interplay between rainfall and host plants is marked by the timing of fruit production and the robust vegetative growth of the host plants, both of which can impact the local fruit fly population (Soares *et al.*, 2023; Dominiak and Follett, 2024). A higher availability of host plants and fruits can influence the number of fruit fly populations. The greater the availability of hosts and fruits, the more likely the fruit fly populations will increase in the area (Hidayat *et al.*, 2023; Setiawan *et al.*, 2024). Environmental factors significantly impact the seasonal population dynamics of *B. carambolae* and *B. papayae*, influencing their reproductive cycles, infestation patterns, and survival rates (Amin *et al.*, 2019; Susanto *et al.*, 2022). The populations of seasonal fruit flies are heavily influenced by environmental conditions, particularly temperature and rainfall. These abiotic factors influence key aspects of fruit fly biology, including reproduction, development, and survival rates. *B. dorsalis* populations tend to increase with rising temperatures, as higher temperatures accelerate development and boost reproductive rates, often leading to population surges. The dynamics of fruit fly populations are also notably

impacted by rainfall. An increase in precipitation leads to better survival and reproductive outcomes, with studies demonstrating a clear positive correlation between rainfall amounts and fruit fly capture rates. It suggests that wetter conditions may support higher fruit fly populations. Besides temperature and rainfall, interspecific competition and ecological interactions play a crucial role in shaping the population structure and adaptability of *Bactrocera carambolae* and *Bactrocera papayae*. These interactions influence their survival, reproductive success, and spatial distribution through mechanisms such as resource competition and competitive displacement (Schutze *et al.,* 2014). Monitoring the capture of fruit flies in traps set up in a particular area provides insights into the population densities of fruit fly species present. Nevertheless, this observation alone does not confirm their interaction with host plants. A study on the habitat use by *B. carambolae* and *Bactrocera dorsalis* in fruit orchards across various geographical regions demonstrated that the flies migrate between microhabitats and other host plants to forage and oviposit, particularly utilizing mangosteen trees for resting and feeding (Kolopaking *et al.,* 2023). The rich diversity of host plant species in varied environments offers an optimal condition for the expansion of fruit fly populations (Hidayat *et al.,* 2023). To mitigate their spread, stringent quarantine measures must be enforced for fruit and vegetable products entering or exiting Indonesia. Moreover, domestic quarantine regulations are crucial to preventing the movement of fruit flies between endemic and non-endemic regions within the country (Larasati *et al.,* 2013; Ariningsih *et al.,* 2022). Furthermore, the type of trapping system and the attractants used for sampling can significantly impact the success of fruit fly capture in traps. More fruit flies are typically captured when traps are placed at the edge of the field rather than within the field (Susanto *et al.,* 2017; Amin *et al.,* 2019; Setiawan *et al.,* 2024). Habitat modification, including deforestation and urbanization, significantly impacts the abundance and distribution of *Bactrocera carambolae* and *Bactrocera papayae*. The alterations in the environment influence the availability of host plants, the conditions of the microclimate, and the interactions within the ecosystem, which collectively determine the dynamics of fruit fly populations. *B. carambolae* prefers humid environments and is more sensitive to deforestation (Raghu *et al.,* 2000). The loss of primary host plants, such as star fruit, leads to population declines in deforested areas. While urbanization often results in diminished host plant diversity, it can simultaneously introduce ornamental and backyard fruit trees, potentially fostering the growth of fruit fly populations.

Fruit flies within fruits infested

Based on the rearing of infested fruits, it was found that star fruit, mango, papaya, guava, and water apple collected from the field were infested by *Bactrocera carambolae* Drew and Hancock and *Bactrocera papayae* Drew and Hancock. Even with the varied landscapes and distant sampling locations, the species of fruit flies that emerged from the infested fruits were identical. In general, the infestation pattern of both fruit fly species tended to increase from the first observation to the twelfth. Interestingly, the number of emerging fruit flies decreased during the ninth observation but rose again from the tenth to the twelfth observations (Fig. 7). This trend is consistent with the quantity of fruit flies collected in field traps (Fig. 4). The number of adult *B. carambolae* emerging from infested fruits was highest in star fruit (39.69 individuals) and lowest in papaya (1.75 individuals). Statistical analysis showed that the number of *B. carambolae* emerging from infested star fruit significantly differed from mango, papaya, and water apple, except for guava. For *B. papayae*, the adult fruit fly population was most abundant in papaya (16.98 individuals) and lowest in water apple (6.48 individuals). The data showed a notable contrast when compared to mango, star fruit, guava, and water apple (Fig. 8). The fruit flies emerging from the infested fruits displayed a pattern akin to that of the fruit fly population found in the traps. High fruit fly populations in the traps were mirrored by high populations emerging from infested fruits.

Consistent with trap capture data, the emergence of *Bactrocera carambolae* and *Bactrocera papayae* from infested fruit was notably higher in star fruit and papaya. It has been noted that the availability of host plants for fruit flies fluctuates based on seasonal factors and the specific species of host plants present. Seasonal fluctuations significantly affect the population dynamics of fruit flies, as evidenced by both trap captures and fruit emergence. The infestations of *B. carambolae* and *B. papayae* align with the fruiting periods of star fruit, mango, guava, water apple, and papaya in West Java Province, coinciding with the rainy season, which exhibits consistent patterns throughout

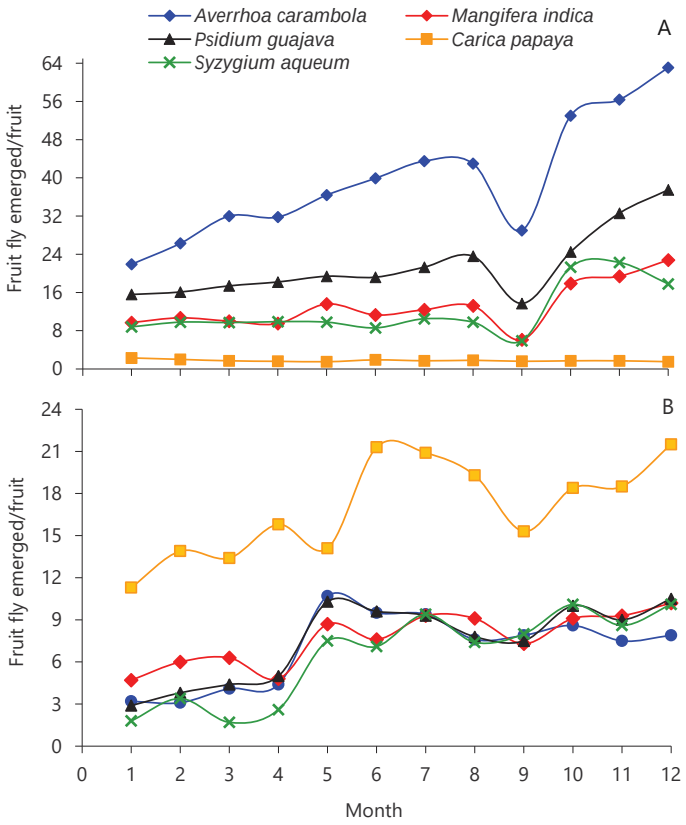


Fig. 7: The seasonal population of adult fruit flies emerged from infested fruit samples of star fruit, mango, guava, water apple, and papaya from fields, caused by *B. carambolae* (a) and *B. papayae* (b).

the months. A significant rise in the populations of *B. carambolae* and *B. papayae* at the beginning of the rainy season results in extensive fruit damage during the mid and late seasons. Infestation rates of *B. carambolae* and *B. papayae* are influenced by both seasonal factors and the availability of host fruits. It was suggests that these two elements independently contribute to the patterns of fruit fly infestations in orchards (Sudiarta *et al.,* 2020; Pogue *et al.,* 2024; Putri *et al.,* 2024). The influence of fruit availability in orchards is nuanced; an increase in the quantity of fruit and variability in ripeness can result in fruit damage from dilution effects, while also facilitating elevated oviposition rates of fruit flies (Muryati *et al.,* 2017; Grechi *et al.,* 2021; Saeed *et al.,* 2022). Economic losses caused by fruit fly infestations vary by region. In Simalungun Regency (North Sumatra, Indonesia), fruit fly damage to orange crops results in losses of 960 United States Dollars per hectare USD /ha) annually. In Indramayu, mango losses amount to 4.42 tons per hectare per year (tons/ ha/y) valued at 4,477 USD/ ha annually. For comparison, fruit fly infestations (*Bactrocera dorsalis*) in mango plantations in Manica Province, Mozambique, cause an average yield loss of approximately 5.65/tons/ha, translating to a financial loss of $US3,428.97/ha (Ariningsih *et al.,* 2022).

Fruit flies preference

The study on the preferences of *B. carambolae* and *B. papayae* for several types of fruit indicates that *B. carambolae* prefers star fruit, while *B. papayae* was more attracted to papaya. It was evidenced by the number of fruit flies that entered the jars containing the fruit and the number of ovipositor punctures. A total of 47.00 individuals of *B. carambolae* chose star fruit, while only 3.75 individuals selected papaya. *B. papayae*, 43.8 individuals chose papaya, with the lowest numbers on star fruit and water apple, each

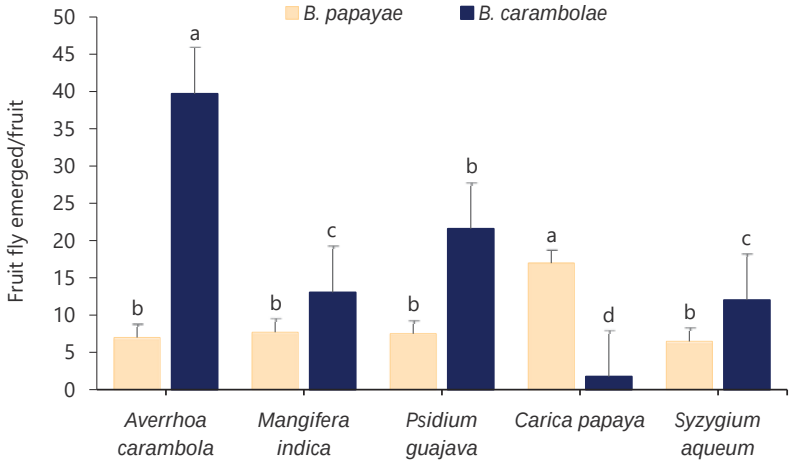


Fig. 8: The mean number of *B. carambolae* and *B. papayae* emerged per fruit sample in infested star fruit, mango, guava, water apple, and papaya orchards. Values are mean ± SE. The means with the same letters for each variable were not significantly different (Tukey's HSD, $P < 0.05$)

of them 6.5. Moreover, the mean count of ovipositor punctures recorded on star fruit was 70, in contrast to the 73 punctures noted on papaya infested with *B. papayae*. Additionally, the highest number of eggs laid by *B. carambolae* was found on star fruit, whereas *B. papayae* laid the most on papaya, with 173.8 and 180.3 eggs, respectively. A correlation was observed between the number of eggs laid and the ovipositor punctures in the fruit; specifically, a higher count of punctures resulted in an increased number of eggs deposited (Fig. 9). As the eggs developed into larvae and pupae, the number of *B. carambolae* pupae were found to be the highest on star fruit and lowest on papaya, with counts of 49.50 and 10.50 pupae, respectively. Interestingly, this pattern was reversed for *B. papayae*. The number of pupae was higher in papaya (42.50 pupae) and lower in star fruit (19.00 pupae) (Table 2). The study also revealed a relationship between the quantity of pupae that emerged and the total number of eggs deposited. As the number of eggs laid increased, so did the number of emerging larvae. The proportion of *B. carambolae* eggs that developed into pupae ranged from 15% to 40%, while for *B. papayae*, it ranged from 21% to 64%.

The percentage of *B. carambolae* adults emerging from pupae was highest on star fruit and lowest on water apple, at 90.40% and 57.37%, respectively, for 7-8 days. Additionally, the percentage of *B. papayae* adults emerging from pupae was highest on papaya (85.95%) and lowest on star fruit (57.90%), with a pupal period of 7-9 days. These findings reveal that each species shows a distinct preference for certain host plants, with the availability of these preferred fruits having a positive correlation with the growth and development of fruit fly populations. Furthermore, among the emerging adults were found that the number of female flies was higher than that of males for both *B. carambolae* and *B. papayae* across all tested host plants. These findings suggest that female fruit flies play a crucial role in sustaining populations in the field. The fruit fly species *Bactrocera carambolae* and *Bactrocera papayae* maintained in jars exhibit different preferences for various host plant species. The results of this study highlight that *B. carambolae* predominantly chooses star fruit, in contrast to *B. papayae*, which exhibits a preference for papaya over alternative fruits. This preference was evidenced by the more significant number of *B. carambolae* entering star fruit and *B. papayae* entering papaya (Fig. 5). Star fruit was identified as the most favored host for oviposition by *B. carambolae*. At the same time, the papaya was the preferred host for *B. papayae*, with the highest number of pupae found in each fruit. Based on their characteristics, it can be inferred that star fruit and papaya are softer than guava, mango, and water apple. The host preferences of these fruit flies are driven by a combination of visual cues and chemical signals emitted by the fruits, which attract them to optimal sites for oviposition. The host selection processes of *B. carambolae* and *B. papayae* are primarily driven by

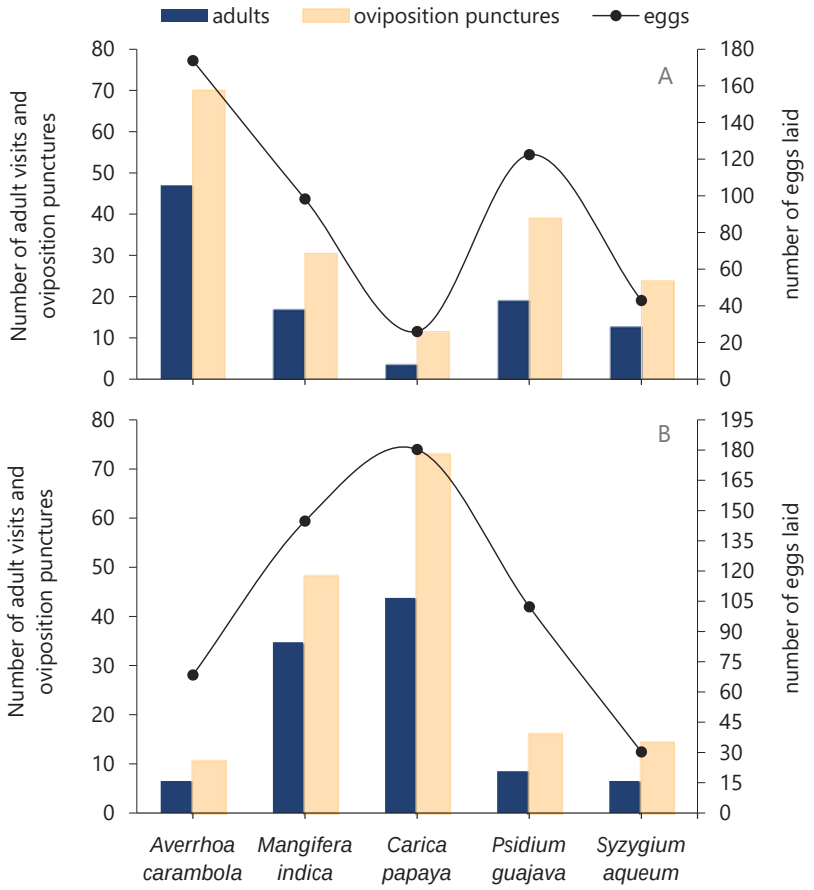


Fig. 9: Number of adults visits, oviposition punctures, and eggs laid of *B. carambolae* (a) and *B. papayae* (b) on several host plants in the laboratory.

Table 2: Fruit fly preference and performance survival from pupa to adult on a several host plant in the laboratory

Host plant	Pupae number	Pupa period (days)	Adults emerged (flies)	Adults emerged (%)	Female number	Male number
Bactrocera carambolae						
A.carambola	49.50 ± 1.44 a	7.25 ± 0.25 ab	44.75 ± 1.54 a	90.40 ± 1.00 a	28.25 ± 0.62 a	15.75 ± 1.37 a
C. papaya	10.50 ± 0.95 c	8.50 ± 0.28 a	6.00 ± 0.40 c	57.70 ± 2.70 c	4.00 ± 0.00 d	2.25 ± 0.25 c
S. aqueum	11.75 ± 0.47 c	8.25 ± 0.25 ab	6.75 ± 0.47 c	57.37 ± 3.11 c	4.50 ± 0.28 d	2.25 ± 0.25 c
M. indica	24.25 ± 0.94 b	7.00 ± 0.48 b	19.25 ± 1.03 b	79.37 ± 2.88 ab	12.00 ± 0.70 b	7.00 ± 0.40 b
P. guajava	20.50 ± 1.04 b	7.75 ± 0.25 ab	15.75 ± 0.47 b	77.15 ± 2.73 b	9.50 ± 0.28 c	6.25 ± 0.47 b
Bactrocera papayae						
A.carambola	19.00 ± 1.08 b	8.75 ± 0.25 a	11.00 ± 0.70 c	57.90 ± 1.81 b	7.25 ± 0.47 c	3.75 ± 0.25 c
C. papaya	42.50 ± 1.19 a	7.25 ± 0.25 b	36.50 ± 0.86 a	85.95 ± 1.66 a	27.50 ± 0.64 a	9.00 ± 0.81 a
S. aqueum	19.50 ± 0.64 b	8.75 ± 0.25 a	14.00 ± 0.40 c	71.95 ± 2.57 b	7.50 ± 0.28 c	6.50 ± 0.28 b
M. indica	39.25 ± 0.94 a	7.25 ± 0.25 b	32.25 ± 0.47 b	82.35 ± 2.90 a	23.25 ± 0.47 b	9.00 ± 0.40 a
P. guajava	22.50 ± 0.64 b	8.50 ± 0.28 a	14.00 ± 1.08 c	62.10 ± 3.95 b	8.75 ± 0.85 c	5.25 ± 0.47 bc

Means (± SE) in one column followed by the same letters have no significant difference at the 5% level according to the Tukey HSD test.

a mix of olfactory and visual factors, the accessibility of host plants, and several environmental influences. The host selection and oviposition behaviors of these fruit fly species are influenced by fruit characteristics, including texture, aroma, odor, color, and nutrient content at all ripeness stages (Fitrah *et al.,* 2021; Grechi *et al.,* 2021; Saeed *et al.,* 2022). Furthermore, the nutritional characteristics of fruits play a significant role in shaping the preferences and growth patterns of fruit flies, which rely on these resources for energy and nourishment throughout their life cycle until they become adults (Theron *et al.,* 2017; Roh *et al.,* 2021; Saeed *et al.,* 2022). These factors play important roles in determining the suitability of a host for egg-laying and following larval development.

This study demonstrated that the quantity of ovipositor punctures on the sampled fruit aligns with the number of fruit flies lured to the host fruit jars, suggesting that the attraction to the host fruit is a precursor to oviposition. The number of ovipositor punctures by *B. carambolae* is higher on star fruit, while *B. papayae* exhibits a more significant number of papaya. There is a direct correlation between the amount of ovipositor punctures and the quantity of eggs that are laid. Star fruit and papaya are selected as oviposition sites by *B. carambolae* and *B. papayae*, respectively, indicating that the texture of these fruits is suitable for egg-laying. It has been found that fruit flies prefer to oviposit on host plants they odor (Roh *et al.,* 2021; Saeed *et al.,* 2022). Several determinants can shape oviposition preferences, including climatic conditions, the specific location, the size and color of the fruit, as well as its flavor (Muryati *et al.,* 2017; Fitrah *et al.,* 2021; Saeed *et al.,* 2022). Larger fruits accompanied by appealing odor, colors, and shapes are more prone to infestation by fruit flies (Roh *et al.,* 2021; Dias *et al.,* 2022). The results indicate that star fruit is the preferred host for *B. carambolae*, while *B. papayae* shows a strong preference for papaya compared to all other tested fruits under laboratory conditions. There were no significant differences observed in the pupal development period across the different fruit hosts. However, water apple was found to be the least preferred compared to star fruit, guava, mango, and papaya. The present study demonstrates a correlation between the number of eggs laid, pupae formation, and adult fruit flies' emergence. In fruits favored and selected as oviposition and pupation sites, more adult fruit flies emerge than other fruits. The homogeneous conditions in the laboratory support the development of fruit flies on host fruits, as biotic environmental factors, such as the population suppression of fruit flies by natural enemies, do not influence them. By providing controlled environmental conditions akin to those in a laboratory, the transformation of pupae into adult fruit flies can be effectively supported (Saeed *et al.,* 2022; Susanto *et al.,* 2022). Additionally, host plants' physical characteristics and chemical compound content significantly influence the development and biology of fruit flies within their hosts (Fitrah *et al.,* 2021; Roh *et al.,* 2021). This phenomenon has the potential to alter the behavior of fruit flies with respect to their feeding, reproduction, mating, and dispersal activities (Saeed *et al.,* 2022; Pogue *et al.,* 2024). The availability of alternative wild and cultivated host plants also significantly influences the survival, dispersal, and population density of *B. carambolae* and *B. papayae*. These fruit flies are polyphagous, meaning they can utilize a wide range of host plants, which has the potential for population expansion and enhances their adaptability (Vargas *et al.,* 2015; Masseliere *et al.,* 2016). Having a range of host plants secures a consistent supply of resources necessary for sustenance and oviposition. The availability of alternative host plants simplifies and facilitates the dispersal of fruit fly populations into new areas. When these flies encounter suitable host plants in different regions, they can form new populations, expanding their geographic range.

Fruit fly parasitoids

During the study, it was found that the natural enemies that developed from the infested fruits were predominantly parasitoids. Notably, these parasitoids were absent from certain host fruits. Four species of parasitoids were identified on several types of fruit, including star fruit, guava, and mango. These parasitoid species were *Biosteres* sp., *Opius* sp., *Diachasmimorpha longicaudata*, and *Fopius arisanus*, all belonging to Hymenoptera and the family Braconidae. These four parasitoids are classified as larval-prepupal endoparasitoids of Tephritid fruit flies, and they emerge from pupae that have been collected from pupae collected from star fruit, mango, and guava. Among the four, *D. longicaudata* and *F. arisanus* had relatively high proportions, accounting for 20.40% and 12.70%, respectively (Table 3). The parasitoid parasitism rate was highest in star fruit (45.99%)

and lowest in mango (17.48%). *D. longicaudata* and *F. arisanus* consistently emerged from each host plant, with varying population and parasitism rates, suggesting competition between these parasitoids in parasitizing *B. carambolae* and *B. papayae* fruit flies. Additionally, several fruit fly pupae experienced mortality during rearing due to factors such as fungal infections, desiccation, or parasitism, especially in guava and mango, where the parasitoid did not successfully develop inside the pupa. Furthermore, these findings highlight the potential of *D. longicaudata* and *F. arisanus* as effective biological control agents, but their success may depend on host fruit availability, competition, and environmental conditions.

The fruit fly parasitoids identified in this study belong to the family Braconidae and include four genera: *Biosteres* sp., *Opius* sp., *D. longicaudata*, and *F. arisanus*. These parasitoids are endobionts that typically parasitize fruit flies during their immature stage and emerge during the pupal stage of fruit fly metamorphosis. The most commonly observed parasitoids in the infested fruit were *D. longicaudata* and *F. arisanus*. These species play a critical role in parasitizing *B. carambolae* and *B. papayae*, exhibiting relatively high parasitism rates compared to other parasitoids such as *Opius* sp. and *Biosteres* sp. The parasitism rates of *D. longicaudata* and *F. arisanus* were highest in *A. carambolae* compared to other hosts, indicating that *A. carambolae* is a more suitable host for developing these parasitoids. Host availability, which includes aspects like fruit morphology, climatic elements (temperature and rainfall), habitat suitability, and the density of fruit flies, played a significant role in shaping parasitoid preferences and parasitism rates. According to Miranda *et al.* (2015), parasitoids preferentially target fruit fly-infested plants with thin and soft skins, such as *A. carambolae*, *P. guajava*, and *M. indica*, as these characteristics facilitate the parasitism of larvae or eggs of the fruit flies. Furthermore, Ovruski *et al.* (2009) indicated that climatic conditions, including rainfall, can impact the presence and parasitism rates of fruit fly parasitoids by affecting their mobility. The presence of the parasitoids *Diachasmimorpha longicaudata* and *Fopius arisanus* on various host plant species, along with varying populations and parasitism rates, indicates competition between these parasitoids for parasitizing *B. carambolae* and *B. papayae*. The interaction between these two parasitoids influences their efficacy as biological control agents against Bactrocera species. *F. arisanus* parasitizes fruit fly eggs, while *D. longicaudata* targets larvae, creating a complementary control strategy (Haryono *et al.,* 2016; Susila and Supartha, 2020; Dias *et al.,* 2022). However, competition may arise if *D. longicaudata* attempts to parasitize hosts already infected by *F. arisanus*. The process of niche partitioning lessens direct competition, and the simultaneous presence of these species can lead to greater efficiency in pest management. Environmental factors and host availability further influence their success, underscoring the need to optimize release strategies for effective and sustainable pest control (Miano *et al.,* 2022). It aligns with the findings by Vargas *et al.* (2013) and Miranda *et al.* (2015), which suggest that interspecific competition can occur between two coexisting parasitoid species. Across all the fruits analyzed, *D. longicaudata* exhibited a higher parasitism rate compared to *F. arisanus*. This finding contrasts with several studies conducted in Bali, which reported lower parasitism rates for *D. longicaudata* compared to *F. arisanus* on various Bactrocera species infesting guava, mango, and star fruit (Haryono *et al.,* 2016; Ardiyanti *et al.,* 2019; Yuliadhi *et al.,* 2022). Successful management of Bactrocera fruit flies

Table 3: Number of parasitoids, fruit flies (± SE), and parasitism levels of fruit fly parasitoids on star fruit, guava, and mango in the field (n=100 pupae)

Variabel		*A.carambolae*	*P. guajava*	*M. indica*
Parasitoid	*Biosteres* sp.	3.30 ± 0.51	0	1.10 ± 0.31
	Opius sp.	7.60 ± 0.51	5.70 ± 0.63	0
	D. longicaudata	20.40 ± 0.21	12.10 ± 0.22	7.40 ± 0.22
	F. arisanus	12.70 ± 0.26	7.60 ± 0.27	8.20 ± 0.25
Fruit flies	*B. carambolae*	42.10 ± 0.30	46.80 ± 0.65	49.40 ± 0.54
	B. papayae	11.40 ± 0.21	16.10 ± 0.41	18.70 ± 0.80
Parasitization (%)		45.99	26.52	17.48
Not emerged (%)		0	9.50 ± 1.05	13.20 ± 0.81

using parasitoids depends on the careful selection of appropriate species, confirming host compatibility, refining release techniques, and taking environmental factors into account. Mass-rearing and augmentation enhance effectiveness by providing a steady parasitoid supply, preserving quality, enabling precise releases, and aligning with the Bactrocera population surge for better suppression and sustainability (Garcia and Ricalde, 2013; Larasati *et al.,* 2013; Miranda *et al.,* 2015). The elevated population and parasitism levels of *D. longicaudata* relative to *F. arisanus* may stem from its improved ability to detect hosts on infested fruits, including those that have dropped to the ground. The parasitism rates of the parasitoids *Biosteres tryoni* and *D. longicaudata* were higher on fallen, decaying fruit infested by fruit flies (Haryono *et al.,* 2016; Setiawan *et al.,* 2024). Additionally, Vargas *et al.* (2013) found that *F. arisanus* exhibited a significantly lower parasitism rate on fallen fruit than on the tree, indicating a preference for oviposition on fruit that remains attached. Furthermore, the parasitism rate of *Fopius* sp. on five species of Bactrocera was lower than that of *Biosteres* sp. (Haryono *et al.,* 2016; Ardiyanti *et al.,* 2019). The successful implementation of environmentally sustainable pest management relies heavily on the detection and identification of parasitoid species associated with pest populations. These findings provide new perspectives into Indonesia's fruit fly management strategies, emphasizing parasitoid augmentation integration with other sustainable control methods for enhanced effectiveness and long-term pest suppression. In agricultural fields, the control of fruit flies remains largely dependent on synthetic insecticides. While these chemicals are crucial for controlling Bactrocera species, increasing insecticide resistance highlights the need for integrated alternative strategies to ensure sustainable and effective pest control (Li *et al.,* 2024; Akram *et al.,* 2024). To enhance integrated pest management (IPM), it is essential to implement monitoring techniques, biological control approaches, and cultural practices that responsibly manage fruit fly populations in an eco-friendly manner. Incorporating remote sensing technology and artificial intelligence enhances pest control's precision, efficiency, and effectiveness while minimizing economic losses and environmental harm (Lello *et al.,* 2023). Educating farmers and stakeholders through IPM training and adopting eco-friendly strategies promotes sustainable fruit fly control and reduces dependence on chemical pesticides (Niassy *et al.,* 2022; Dias *et al.,* 2022; Dominiak and Follett, 2024). Utilizing fruit fly traps that are baited with methyl eugenol represents one of the most affordable and sustainable methods for monitoring. Data collected from these traps can support the development of predictive models, strengthen early warning systems, and ultimately decrease crop damage and reliance on chemical control measures.

CONCLUSION

This study confirms that *Bactrocera carambolae* and *Bactrocera papayae* are the dominant fruit fly species affecting fruit cultivation in Indonesia, particularly in West Java Province. In their respective environments, both species reveal specific host preferences; *B. carambolae* is particularly attracted to star fruit, whereas *B. papayae* tends to favor papaya. Laboratory experiments further confirm that fruit characteristics such as texture, odor, and nutrient content influence fruit fly oviposition and development. Star fruit and papaya were identified as the most suitable hosts for *B. carambolae* and *B. papayae*, respectively, as these fruits supported higher egg-laying, pupation, and adult emergence rates compared to other fruit types. urthermore, the presence of host plants is essential in influencing infestation patterns, which in turn has a significant impact on the dynamics of fruit fly populations. Regions that have a plentiful supply of preferred host fruits typically encounter elevated infestation rates, since these plants supply crucial resources for the reproduction, development of larvae, and overall survival of fruit flies. The presence of suitable host plants attracts adult fruit flies and sustains population growth by offering optimal conditions for egg-laying and larval nourishment. The significant reliance on the availability of host plants highlights the necessity for strategic pest management strategies, including crop diversification and synchronized harvesting, to interrupt the breeding cycles of fruit flies and effectively mitigate infestations. Ecological factors, particularly rainfall and temperature, also play a pivotal role in regulating the population dynamics of these fruit fly species. *Bactrocera carambolae* reaches peak abundance during the rainy season, benefiting from increased moisture and humidity, while *Bactrocera papayae* thrives in warmer conditions, indicating a strong preference for higher temperatures. The evident connection between

fruit fly populations and environmental variables emphasizes the important role that climate plays in their distribution and growth patterns. Increased rainfall fosters favorable conditions for *B. carambolae* by enhancing host fruit availability and improving larval survival rates. In contrast, elevated temperatures accelerate the development, reproduction, and overall abundance of *B. papayae*. These findings highlight the necessity of integrating climatic variables into fruit fly management approaches, especially in areas undergoing seasonal variations in rainfall and temperature. Additionally, four parasitoid species were identified, with *Diachasmimorpha longicaudata* and *Fopius arisanus* exhibiting notably high parasitism rates in the field. This suggests that these parasitoids could serve as significant mortality factors for *B. carambolae* and *B. papayae*. The conclusions drawn from this study underscore the importance of adopting effective strategies for managing fruit flies in the agricultural sector focused on fruit production. Monitoring techniques, such as methyl eugenol traps, have proven effective in tracking and reducing fruit fly populations. To effectively manage pests, an integrated approach should evaluate seasonal variations, host plant preferences, and environmental factors, aiming to reduce infestations, minimize agricultural losses, and foster ecological sustainability. Further research is recommended to study and culture the four parasitoid species of *B. carambolae* and *B. papayae* found in West Java Province, to optimize augmentative biological control strategies for fruit flies.

AUTHOR CONTRIBUTIONS

D. Koswanudin conceptualized the research idea, designed the study, conducted investigations, performed literature reviews, curated data, and secured funding. H. Widyanto contributed to the design and conceptualization of the manuscript, conducting investigations, curating data, performing literature reviews, analysis, and interpretation of data. D. Hutapea contributed to the acquisition of data, analysis and interpretation of data, statistical analysis, and manuscript preparation and helped improve the manuscript. Wawan contributed to conducting investigations, acquiring data, and drafting the manuscript. R. Yuniawati contributed to performing literature reviews, curating data, and obtaining funding. V.N.O. Subagyo contributed to the data visualization and manuscript preparation and its improvement. S. Utami contributed to the acquisition of data, analysis, interpretation of data, statistical analysis, and drafting of the manuscript, and helped improve the manuscript. I. M. Samudra contributed to designing the study, supervising, preparing, and improving the manuscript. W. Darwiati performed the literature reviews and contributed to manuscript preparation.

ACKNOWLEDGEMENT

Authors thank Dr. Mastur for his assistance with laboratory facilities for conducting research, and also thank Dr. Karden Mulya for his constructive criticism of this manuscript.

CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
°C	Degree Celsius

ANOVA	Analysis of variance
AQIS	Australian Quarantine and Inspection Service
cm	Centimeters
CSAI	Central Statistic Agency of Indonesia
Fig.	Figure
GDP	Gross domestic product
GLM	Generalized linear model
h	Hours
ha	Hectare
HSD	Honestly Significant Difference
IPM	Integrated pest management
m^2	Square meters
mm	Millimeters
pH	Potential of Hydrogen
R2+3	Wing vein ending at the anterior apical third of the wing
R^2	R squared (the coefficient of determination)
SE	Standard error
Tav	Average temperature
Tmax	Maximum temperature
Tmin	Minimum temperature
USD	United States Dollar
w/w	Weight per weight
X1	Maximum temperature
X2	Minimum temperature
X3	Average temperature
X4	Rainfall
y	Year

REFERENCES

Adnyana, I.M.M.; Susila, I.W.; Elysabet, L., (2023). Komposisi populasi lalat buah (Diptera: Tephritidae) dan parasitoid yang berasosiasi dengan tanaman mangga (*Mangifera indica* L.) di beberapa Kabupaten Provinsi Bali. Agrotrop: J. Agric. Sci., 13(1): 137–149 (**13 pages**).

Aketarawong, N.; Isasawin, S.; Sojikul, P.; Thanaphum, S., (2015). Gene flow and genetic structure of *Bactrocera carambolae* (Diptera, Tephritidae) among geographical differences and sister species, *B. dorsalis*, inferred from microsatellite DNA data. Zookeys. (540): 239–272 (**24 pages**).

Akram, W.; Hussain, A.; Abbas, Q.; Abbas, A., (2024). Insecticidal potential of botanical extracts for management of, the oriental fruit fly, Bactrocera dorsalis (Diptera: Tephritidae). J. Baz., 85: 63 (**12 pages**).

Amin, M.R.; Nancy, N.P.; Miah, M.R.U.; Miah, M.G.; Kwon, O.; Suh, S.J., (2019). Fluctuations in fruit fly abundance and infestation in sweet gourd fields in relation to varied meteorological factors. Entomol. Res., 49(5): 223–228 (**6 pages**).

Ardiyanti, R.M.; Maryana, N., Pudjianto, P., (2019). Keanekaragaman lalat buah (Diptera: Tephritidae) dan parasitoidnya di Taman Buah Mekarsari, Cileungsi, Bogor. J. Entomol. Indones., 16(2): 65–74 (**10 pages**).

Ariningsih, E.; Ashari; Saptana; Saliem, H.P.; Septanti, K.S., (2022). Economic loss and control management of fruit fly infestation on horticultural commodity in Indonesia. Forum Penelitian Agro Ekonomi. 40 (2): 71-89 (**19 pages**).

CSAI, (2024a). Economic statistic: Fruits production in 2023. Central Statistic Agency of Indonesia.

CSAI, (2024b). Economic Statistic: Fruit exports to several destination countries in 2023. Central Statistic Agency of Indonesia.

Danjuma, S.; Boonrotpong, S.; Thaochan, N.; Satasook, C., (2014). Seasonality of the Asian papaya fruit fly *Bactrocera papayae* Drew and Hancock (Diptera: Tephritidae) on guava *Psidium guajava* in Peninsular Thailand. J. Entomol. Zool., 2(5): 276–284 (**9 pages**).

Danjuma, S.; Thaochan, N.; Permkam, S.; Satasook, C., (2014). Effect of temperature on the development and survival of immature stages of the carambola fruit fly, *Bactrocera carambolae*, and the Asian papaya fruit fly, *Bactrocera papayae*, reared on guava diet. J. Insect Sci., 14(126): 1–16 (**16 pages**).

Deus, E.D.; Passos, J.; Sauers-Muller, A.V.; Jesus, C.; Silva, J.G.; Adaime, R. (2024)., Phylogeography of the invasive fruit fly species *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) in South America. Insects. 15(12): 949 (**14 pages**).

Dias, N.P.; Montoya, P.; Nava, D.E., (2022). A 30-year systematic review reveals success in tephritid fruit fly biological control research. Entomol. Exp. Appl., 170(5): 370–384 (**15 pages**).

Dominiak, B.C.; Follett, P.A., (2024). Review of host use and host reproduction number for new world fruit flies (Diptera: Tephritidae) to optimise surveillance, management and trade. Int. J. Trop. Insect Sci., 44(2): 595–635 (**41 pages**).

Fitrah, R.; Pranowo, D.; Suputa, S., (2021). Oviposition preference of *Bactrocera dorsalis* Hendel (Diptera: Tephritidae) on different fruit in snake fruit orchard. J. Perlindungan Tanaman Indonesia, 24(2): 224–228. (**5 pages**).

Garcia, F.R.M., Ricalde, M.P. (2013). Augmentative biological control using parasitoids for fruit fly management in Brazil. Insects. 4(1): 55-70 (**16 pages**).

Goulet, H.; Huber, J., (1993). Hymenoptera of the world: An identification guide to families. Centre for Land and Biological Resources Research Agriculture Canada, Ottawa, Canada.

Grechi, I.; Preterre, A.L.; Caillat, A.; Chiroleu, F.; Ratnadass, A., (2021). Linking mango infestation by fruit flies to fruit maturity and fly pressure: A prerequisite to improve fruit fly damage management via harvest timing optimization. Crop Prot., 146: 105663 (**10 pages**).

Haryono, T.; Sastrahidayat, I.R.; Mudjiono, G.; Himawan, T., (2016). The exploration of fruit flies Bactrocera (Diptera:Tephritidae) and its parasitoid in Madura Island Regions. Berkala Penelitian Hayati. 21(2), 75–80 (**6 pages**).

Hasyim, A.; Muryati, M.; de Kogel, W.J., (2008). Population fluctuation

of adult males of the fruit fly, *Bactrocera tau* Walker (Diptera: Tephritidae) in passion fruit orchards in relation to abiotic factors and sanitation. Indones. J. Agric. Sci., 9(1): 29–33 (**5 pages**).

Hasyim, A.; Muryati.; de Kogel, W.J., (2006). Efektivitas model dan ketinggian perangkap dalam menangkap hama lalat buah jantan, *Bactrocera spp*. J. Hortikultura. 16(4): 314–320 (**7 pages**).

Hidayat, P.; Adilah, N.B.; Maryana, N.; Suputa., (2023). Review of species, host plants, and distribution of fruit flies (Diptera: Tephritidae) in Indonesia. IOP Conference Series: Earth Environ. Sci., 1208: 012018 (**7 pages**).

Hudiwaku, S.; Himawan, T.; Rizali, A., (2021). Diversity and species composition of fruit flies (Diptera: Tephritidae) in Lombok Island, Indonesia. Biodiversitas. 22(10), 4608–4616 (**9 pages**).

Jaffar, S.; Rizvi, S.A.H.; Lu, Y., (2023). Understanding the invasion, ecological adaptations, and management strategies of *Bactrocera dorsalis* in China: a review. Horticulturae 9(9): 1004 (**23 pages**).

Kolopaking, B.; Rizali, A.; Affandi, A.; Hudiwaku, S.; Himawan, T., (2023). Population dynamic and distribution of *Bactrocera carambolae* and *Bactrocera dorsalis* in orchard habitat in different geographical areas. Res. J. Life Sci., 10(1): 1–12 (**12 pages**).

Larasati, A.; Hidayat, P.; Buchori, D., (2013). Diversity and distribution of fruit flies Tribe Dacini (Diptera: Tephritidae) in Bogor district and its surrounding area. Indonesian Journal of Entomology. 10(2):51-59 (**9 pages**).

Lello, F.; Dida, M.; Mkiramweni, M.; Matiko, J.; Akol, R.; Nsabagwa, M.; Katumba, A., (2023). Fruit fly automatic detection and monitoring techniques: A review. Smart Agr.Technol., 5: 100294 (**17 pages**).

Li, D.; Cai, X.; Qi, Y.; Lu, Y.; Li, X., (2024). Lethal, Sublethal, and offspring effects of fluralaner and dinotefuran on three species of Bactrocera fruit flies. Insects. 15(6): 440. (**12 pages**).

Masseliere, M.C.; Ravigné, V.; Facon, B.; Lefeuvre, P.; Massol, F.; Quilici, S.; Duyck, P.F., (2016). Changes in phytophagous insect host ranges following the invasion of their community: Long-term data for fruit flies. Ecol. Evol., 7: 5181–5190 (**10 pages**).

Miano, R.N.; Mohamed, S.A.; Cheseto, X.; Ndlela, S.; Biasazin, T.D.; Yusuf, A.A.; Rohwer, E.; Dekker, T., (2022). Differential responses of *Bactrocera dorsalis* and its parasitoids to headspaces of different varieties of tree-attached mango fruits and the associated chemical profiles. Front. Ecol. Evol., 14: 1021795 (**21 pages**).

Miranda, M.; Sivinski, J.; Rull, J., Cicero, L.; Aluja, M., (2015). Niche breadth and interspecific competition between *Doryctobracon crawfordi* and *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae), native and introduced parasitoids of *Anastrepha spp* fruit flies (Diptera: Tephritidae). Biol. Control. 82: 86–95 (**10 pages**).

Muryati, M.; Trisyono, Y.A.; Witjaksono, W.; Wahyono, W., (2017). Oviposition deterrent of *Bactrocera carambolae* resulted from eggs deposition on mango. Agrivita. 39(2): 201–213 (**13 pages**).

Niassy, S.; Murithii, B.; Omuse, E.R.; Kimathi, E.; Tonnang, H.; Ndlela, S.; Mohamed, S.; Ekesi, S., (2022). Insight on fruit fly IPM technology uptake and barriers to scaling in Africa. Sustainability. 14(5): 2954 (**25 pages**).

Ovruski, S.M.; Schliserman, P.; Nunez-Campero, S.R.; Orono, L.E.; Bezdjian, L.P.; Albornoz-Medina, P.; van Nieuwenhove, G.A., (2009). A survey of hymenopterous larval-pupal parasitoids associated with *Anastrepha fraterculus* and *Ceratitis capitata* (Diptera: Tephritidae) infesting wild guava (*Psidium guajava*) and peach (*Prunus persica*) in the southernmost section of the Bolivian Yungas forest. Florida Entomologist. 92(2): 269–275 (**7 pages**).

Pogue, T.; Malod, K.; Weldon, C.W., (2024). Effects of physiological status and environmental factors on the lure responses of three pest fruit fly species (Diptera: Tephritidae). J. Chem. Ecol., 50: 679–700 (**22 pages**).

Putri, Y.D.; Gunadi, R.; Pranowo, D.; Affandi, A.; Suputa., (2024). Population dynamic of fruit fly pests *Bactrocera spp* in salacca orchard in relation to host plants and climate factors. Agrivita. 46(1): 1–14 (**14 pages**).

Qin, Y.J.; Krosch, M.N.; Schutze, M.K., Zhang, Y.; Wang, X.; Prabhakar, C.S.; Susanto, A.; Hee, A.K.W.; Ekesi, S.; Badji, K.; Khan, M.; Wu, J.; Wang, Q.; Yan, G.; Zhu,L.; Zhao, Z.; Liu, L.; Clarke, A.R.; Li, Z., (2018). Population structure of a global agricultural invasive pest, *Bactrocera dorsalis* (Diptera: Tephritidae). Evol. Appl., (11):1990-2003 (**23 pages**).

Raghu, S.; Clarke, A.R.; Drew, R.; Hulsman, K., (2000). Impact of habitat modification on the distribution and abundance of fruit flies (Diptera: Tephritidae) in Southeast Queensland. Popul. Ecol., 42(2): 153-160 (**8 pages**).

Roh, G.H.; Kendra, P.E.; Cha, D.H., (2021). Preferential attraction of oviposition-ready oriental fruit flies to host fruit odor over protein food odor. Insects. 12(10): 909 (**12 pages**).

Saeed, M.; Ahmad, T.; Alam, M.; Al-Shuraym, L.A.; Ahmed, N.; Alshehri, M.A.; Ullah, H.; Sayed, S.M., (2022). Preference and performance of peach fruit fly (*Bactrocera zonata*) and Melon fruit fly (*Bactrocera cucurbitae*) under laboratory conditions. Saudi J. Biol. Sci., 29(4): 2402–2408 (**7 pages**).

Schutze, M.K.; Aketarawong, N.; Amornsak, W.; Armstrong, K.F.; Augustinos, A.A.; barr, N.; ..Clarke, A.R., (2014). Synonymization of key pest species within the *Bactrocera dorsalis* species complex (Diptera: Tephritidae): taxonomic changes based on a review of 20 years of integrative morphological, molecular, cytogenetic, behavioural and chemoecological data. Syst. Entomol., 40 (2): 456-471 (**16 pages**).

Setiawan, Y.; Hamdoen, F.M.; Muhammad, F.N.; Hata, K.; Tarno, H.; Wang, J., (2024). Species composition of Bactrocera fruit flies (Diptera: Tephritidae) and their parasitoids on horticultural commodities in Batu City and Malang District, East Java, Indonesia. Biodiversitas. 25(1): 305–311 (**7 pages**).

Shaw, M.; Huddleston, T., (1991). Classification and Biology of Braconid Wasps. In W. Dolling & R. Askew (Eds.), Handbooks for the Identification of British Insects. Royal Entomol. Soc.,

Siwi, S.S.; Hidayat, P.; Suputa, S., (2006). Taksonomi dan Bioekologi Lalat Buah Penting di Indonesia (Diptera: Tephritidae) (1st ed.). Bioteknologi dan Sumberdaya Genetik Pertanian, Kementerian Pertanian, Jakarta.

Soares, G.K.A.; Fidelis, E.G.; Farias, E.S.; Rodrigues, G.S.; Paes, J.L.A., (2023). Range expansion and population dynamics of *Bactrocera carambola* in Roraima, Brazil. Crop Prot., 165: 106167 (**8 pages**).

Sudiarta, I.P.; Wijayanti, F.E., Temaja, I.G.R.M.; Wirya, G.N.A.S.; Sumirtha, K.; Selangga, D.G.W., (2020). Present status of fruit fly *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) in Bali Island, Indonesia. International Conference and the 10th Congress of the Entomological Society of Indonesia (**6 pages**).

Susanto, A.; Faradilla, M.G.; Sumekar, Y.; Yudistira, D.H.; Murdita, W.; Permana, A.P.; Djaya, L.; Putri, S.N.S., (2022). Effect of various depths of pupation on adult emergence of interspecific hybrid of *Bactrocera carambolae* and *Bactrocera dorsalis*. Sci. Rep., 12: 4235 (**7 pages**).

Susanto, A.; Fathoni, F.; Atami, N.I.N.; Tohidin, T., (2017). Fluktuasi populasi lalat buah (*Bactrocera dorsalis*) (Diptera: Tephritidae) pada pertanaman pepaya di Desa Margaluyu, Kabupaten Garut. Agrikultura. 28(1): 32–38 (**7 pages**).

Susanto, A.; Pratyadhiraksana, G.; Yudistira, D.H.; Suganda, T.; Putri, S.N.S., (2022). Interspecific mating effect of *Bactrocera carambolae* and *Bactrocera dorsalis* on its fecundity, survival and morphologies. Pak. J. Biol. Sci., 25(7): 654–659 (**6 pages**).

Susila, I.W.; Supartha, I.W., (2020). Jenis dan peranan parasitoid dalam mengendalikan populasi lalat Buah (*Bactrocera dorsalis* Complex.) (Diptera: Tephritidae) yang menyerang buah mangga (*Mangifera indica* L) di Kabupaten Buleleng. Agrotrop: J. Agric. Sci., 10(1): 29–38 (**13 pages**).

Theron, C.D.; Manrakhan, A.; Weldon, C.W., (2017). Host use of the oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), in South Africa. J. Appl. Entomol., 141(10): 810–816 (**7 pages**).

Vargas, R.I.; Pinero, J.C.; Leblanc, L., (2015). An overview of pest species of bactrocera fruit flies (Diptera: Tephritidae) and the integration of biopesticides with other biological approaches for their management with a focus on the pacific region. Insects 6(2): 297-318 (**21 pages**).

Vargas, R.I.; Stark, J.D.; Banks, J., Leblanc, L.: Manoukis, N.C.; Peck, S., (2013). Spatial dynamics of two oriental fruit fly (Diptera: Tephritidae) parasitoids, *Fopius arisanus* and *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae), in a Guava Orchard in Hawaii. Environ. Entomol., 42(5): 888–901 (**14 pages**).

Vargas, R.I.; Walsh, W.A.; Kanehisa, D.; Stark, J.D.; Nishida, T., (2000). Comparative demography of three hawaiian fruit flies (Diptera: Tephritidae) at alternating temperatures. Ann. Entomol. Soc. Am., 93(1): 75 – 81 (**7 pages**).

Yuliadhi, K.A.; Susila, I.W.; Supartha, I.W., Sultan, A.; Yudha, I.K.W.; Utama, I.W.E.K.; Wiradana, P. A., (2022). Interaction of parasitoids associated with fruit flies attacking star fruit (*Averrhoa carambolae*) in Denpasar City, Bali Province, Indonesia. IOP Conference Serirs: Earth Environ. Sci., 980(1): 980 012051 (**7 pages**).

AUTHOR (S) BIOSKETCHES

Koswanudin, D., Ph.D., Senior researcher, Research Center for Applied Zoology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *dodi008@brin.go.id*
- ORCID: 0009-0006-9659-000X
- Web of Science ResearcherID: NA
- Scopus Author ID: 57226796149
- Homepage: http://brin.go.id/

Widyanto, H., M.Sc., Junior Researcher, Research Center for Applied Zoology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *hery012@brin.go.id*
- ORCID: 0000-0002-5385-2317
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: http://brin.go.id/

Hutapea, D., Ph.D., Junior Researcher, Research Center for Horticulture, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *dedi026@brin.go.id*
- ORCID: 0000-0002-1801-1918
- Web of Science ResearcherID: ITV-8701-2023
- Scopus Author ID: 57496718100
- Homepage: http://brin.go.id/

Wawan., M.Sc., Junior Researcher, Research Center for Applied Zoology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *wawa024@brin.go.id*
- ORCID: 0009-0008-2205-1606
- Web of Science ResearcherID: NA
- Scopus Author ID: 58292582700
- Homepage: http://brin.go.id/

Yuniawati, R., M.Sc., Junior Researcher, Research Center for Applied Zoology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *rafi004@brin.go.id*
- ORCID: 0000-0003-4943-9578
- Web of Science ResearcherID: NA
- Scopus Author ID: 57212873420
- Homepage: http://brin.go.id/

AUTHOR (S) BIOSKETCHES

Subagyo, V.N.O., M.Sc., Junior Researcher, Research Center for Applied Zoology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *vani001@brin.go.id*
- ORCID: 0000-0003-2350-7739
- Web of Science ResearcherID: NA
- Scopus Author ID: 57826691200
- Homepage: http://brin.go.id/

Utami, S., Ph.D., Senior researcher, Research Center for Applied Zoology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *sriu004@brin.go.id*
- ORCID: 0000-0001-8674-2299
- Web of Science ResearcherID: NA
- Scopus Author ID: 57421746700
- Homepage: http://brin.go.id/

Samudra, I.M., Ph.D., Senior researcher, Research Center for Applied Zoology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *imad026@brin.go.id*
- ORCID: 0009-0001-8032-5774
- Web of Science ResearcherID: NA
- Scopus Author ID: 57225250754
- Homepage: http://brin.go.id/

Darwiati, W., M.Sc., Senior Researcher, Research Center for Applied Zoology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
- Email: *wida.darwiati@brin.go.id*
- ORCID: 0000-0032-3237-5187
- Web of Science ResearcherID: NA
- Scopus Author ID: 57213352896
- Homepage: http://brin.go.id/

HOW TO CITE THIS ARTICLE

Koswanudin, D.; Widyanto, H.; Hutapea, D.; Wawan, Yuniawati, R.; Subagyo, V.N.O.; Utami, S.; Samudra, I.M.; Darwiati, W., (2025). Ecological population dynamics, host preferences, and associated parasitoids of Bactrocera carambolae and Bactrocera papayae on fruits. Global J. Environ. Sci. Manage., 11(2): 631-652.

DOI: 10.22034/gjesm.2025.02.15

URL: https://www.gjesm.net/article_721255.html

Global J. Environ. Sci. Manage. 11(2): 653-676, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Sesbania grandiflora activated carbon as a high-efficiency stable and reusable adsorbent for sustainable fluoride removal

D. Sivakumar[1,*], M. Perarul Selvan[1], J. Nouri[2,3], M. Juhi Jabin[1], S. Priyanka[1], G. Madhubala[1]

[1] *Department of Agricultural Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu, India*

[2] *Department of Environmental Health Engineering, Tehran University of Medical Sciences, Tehran, Iran*

[3] *1137 Spectrum, Irvine, Orange County 92618 USA*

ARTICLE INFO

Article History:
Received 09 December 2024
Revised 12 February 2025
Accepted 14 March 2025

Keywords:
Adsorption isotherms
Fluoride removal
Groundwater treatment
Kinetics and mechanisms
Sesbania grandiflora activated carbon

ABSTRACT

BACKGROUND AND OBJECTIVES: Excess fluoride in groundwater poses environmental and public health risks, causing skeletal and dental fluorosis. Standard defluoridation techniques encounter difficulties concerning their expense, efficiency, and potential for reuse. This study assesses the effectiveness of *Sesbania grandiflora* activated carbon as a reliable and reusable adsorbent for fluoride, emphasizing its characterization, ideal adsorption parameters, and reusability.

METHODS: *Sesbania grandiflora* activated carbon was synthesized and characterized using fourier transform infrared spectroscopy, scanning electron microscopy, energy dispersive x-ray spectroscopy, and x-ray diffraction to assess structural integrity and surface interactions. Batch adsorption experiments were conducted by varying particle size (up to 2.360 millimeter), dosage (2–10 grams), agitation speed (100–500 revolution per minutes), and contact time (up to 140 minutes) to determine the optimal conditions for fluoride removal. Freundlich and Langmuir models were employed to analyze the adsorption isotherms and kinetics. Furthermore, the reusability was tested over five regeneration cycles with 0.1 mole sodium hydroxide.

FINDINGS: Fourier transform infrared spectroscopy revealed interactions between fluoride ions and surface functional groups. The analysis using scanning electron microscopy indicated a porous structure characterized by pore sizes between 0.5 and 5 microns, which exhibited a smoother appearance following adsorption, thus validating the absorption of fluoride. Energy dispersive x-ray spectroscopy showed before treatment, *Sesbania grandiflora* activated carbon had 78.3 percent carbon and 16.5 percent oxygen, while after treatment, carbon increased to 78.8 percent, oxygen to 17.1 percent, and sodium rose to 2.1 percent, with phosphorus and sulphur undetected. X-ray diffraction confirmed that activated carbon from *Sesbania grandiflora* remained mostly amorphous, with crystallinity increasing from 17.2 percent to 17.4 percent. The study revealed that the best adsorption conditions include a particle size of 2.360 millimeters, a dosage of 8 grams, an agitation speed of 300 revolutions per minute, and a contact duration of 120 minutes, which together achieved a fluoride removal efficiency of 89.3 percent. Adsorption followed the Freundlich isotherm (coefficient of determination is 0.9976), suggesting a multilayer heterogeneous adsorption process. Pseudo second order kinetics (coefficnet of determination is 0.9988) confirmed chemisorption as the dominant mechanism. *Sesbania grandiflora* activated carbon maintained 78.3 percent efficiency after five regeneration cycles, demonstrating good reusability.

CONCLUSION: The activated carbon obtained from *Sesbania grandiflora* is an exceptionally efficient and stable adsorbent for fluoride removal in groundwater, offering reusability while preserving its structural integrity and effectiveness. Its potential for scalable, sustainable water treatment warrants further study on scale-up, hybrid integration, and enhanced regeneration techniques.

DOI: 10.22034/gjesm.2025.02.16

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
49	10	5

*Corresponding Author:
Email: *d.sivakumar@klu.ac.in*
Phone: +9197 9097 3774
ORCID: 0000-0001-5228-0145

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

The crust of the earth, the air, the soil, the water, and a range of foods are natural sources of fluoride (Onipe *et al.,* 2020). High concentrations of fluoride in soil from irrigation can lead to reduced fertility and lower agricultural yields. Furthermore, increased fluoride levels in aquatic environments endanger aquatic life, and contaminated groundwater may not unsuitable for domestic purposes. Over consumption of fluoride in food and water can cause dental fluorosis in children, leading to tooth discoloration and pitting. Long-term exposure may result in skeletal fluorosis, damaging bones and joints, and potentially causing hypothyroidism (Mallishery *et al.,* 2020). An excessive amount of fluoride intake can impede iodine absorption, which may lead to hypothyroidism, renal toxicity, compromised kidney function, and neurobehavioral concerns, including a decline in intelligence quotient (IQ), memory issues, and learning challenges (Singh and Singh, 2021). Elevated fluoride concentrations in plants can stunt development, lower agricultural yields, and induce necrosis or discolouration of the leaves, which can upset nearby ecosystems and food sources (Kumari *et al.,* 2024). Fluoride contamination in groundwater is a major issue in Tamil Nadu, particularly in drought-prone districts like Dharmapuri, Krishnagiri (Kavisri and Moovendhan, 2024), and hard rock terrains of Madurai (Thivya *et al*., 2017), where fluoride levels often exceed health limits due to geological factors. Recent assessments show that about 9.04% of groundwater samples in India exceed permissible fluoride limits, with Tamil Nadu among the most affected states. Reports indicate that fluoride levels in Erode and Coimbatore are elevated, contributing to health concerns like dental and skeletal fluorosis, especially in regions where the concentration exceeds the 1 milligram per liter (mg/L) threshold established by the Bureau of Indian Standards (BIS) (Kumar 2021). The Hogenakkal integrated drinking water project, implemented by the Tamil Nadu Water Supply and Drainage Board with funding from the Japan Bank for International Cooperation, provides safe drinking water to affected districts using Cauvery river water (Gousalya *et al*., 2023). Current activities encompass groundwater monitoring, awareness campaigns for the public, and techniques for defluoridation. Nevertheless, enduring challenges call for additional sustainable water management strategies and policy interventions to ensure the protection of public health. The World Health Organization (WHO) recommends a maximum fluoride concentration of 1.5 mg/L in drinking water to prevent health risks. It is vital to decrease fluoride concentrations in groundwater to safeguard environmental integrity and public health. Achieving safe and sustainable groundwater utilization demands the implementation of efficient treatment processes, diligent monitoring, and sound policy frameworks. Various traditional and advanced methods, including precipitation-based and alumina-activated adsorption, have been used for fluoride removal (Wang *et al.,* 2023), reverse osmosis (Ousman *et al.,* 2023), ion exchange (Addar *et al.,* 2024), dialysis by electrodialysis (Imai *et al.,* 2017), precipitation and coagulation (Solanki, *et al.,* 2021), nalgonda method (Divyadeepika *et al.,* 2024), adsorption of bone char (Huyen *et al.,* 2023), adsorption activated carbon (Takmil), nano-separation (Ghomashi *et al.,* 2020), the process of distillation and adsorption to different adsorbents (Iwar and Ugwudike 2022). Among various techniques, adsorbent materials like activated carbon sourced from natural and waste origins have proven to be the most effective in eliminating fluoride ions. The recent studies also showed that the activated carbon derived from materials like lemon peels (Amaibi *et al*., 2024) and hazelnut shells (Al-Musawi *et al*., 2024) has demonstrated effective fluoride removal, with improvements noted through modifications and hybrid treatments (Bakhta *et al*., 2022; Bonyadi *et al*., 2019). A study conducted by Fito *et al*. (2019) and Chukka *et al*. (2022) highlights the significance of enhancing the properties of biomass-derived activated carbon to improve its effectiveness in removing fluoride from water sources, a method that is both highly efficient and cost-effective (Bakhta *et al*., 2022; Chukka *et al*., 2022). The consistent observation across these studies is the importance of enhancing adsorbent properties, such as surface area, functional groups, and pore structure, to improve fluoride removal efficiency in terms of both adsorption capacity and reusability. The choice of fluoride removal technique for groundwater is influenced by several aspects; including fluoride content, water chemistry, cost, and resource availability. Due to their effectiveness and flexibility in different scenarios, techniques such as activated alumina adsorption, reverse osmosis, and ion

exchange are commonly used (Adam *et al.,* 2022). Adsorption techniques are quite successful in eliminating fluoride from groundwater, especially when using activated alumina and bone char (Kennedy and Arias-Paic, 2020). The adsoption techniques have benefits such as ease of use, affordability, and the capacity to treat different fluoride concentration levels. These approaches are flexible and can be adjusted in scale, making them ideal for a wide array of water treatment demands, from small to big (Jayashree *et al.,* 2020). Traditional treatment methods are effective, but adsorption techniques may have higher environmental impacts and operational costs. Adsorption offers a cost-effective, eco-friendly solution for fluoride removal, especially in water-scarce areas. The effectiveness of adsorption is influenced by critical factors such as the characterization of the adsorbent, the design of experimental procedures, the methods of regeneration, and the modeling of kinetics involved in adsorption. Activated carbon from agricultural by-products is a popular choice due to its large surface area and high fluoride removal efficiency. Activated dried palmyrah (*Borassus flabellifer*) nut shells carbon (Senewirathna *et al.,* 2022), date palm (*Phoenix dactylifera*) stems carbon (Bakhta *et al.,* 2022) and raffia palm shell (*Raphia farinifera*) activated carbon-aluminium oxide (Iwar and Ugwudike, 2022) have been investigated for their fluoride-adsorption capacity. *Sesbania grandiflora (*S. *grandiflora)* has been selected as the biomass material for fluoride removal from groundwater due to its exceptional physicochemical properties, widespread availability, and the environmental benefits it offers in comparison to other biomass options. It possesses a highly porous structure and abundant functional groups such as hydroxyl and carboxyl, which enhance its fluoride adsorption capacity (Palodkar *et al*., 2017; Tan *et al*., 2020). Additionally, S. *grandiflora* is a fast-growing leguminous tree that thrives in diverse climatic conditions with minimal agricultural input, ensuring a sustainable and cost-effective raw material supply (Varol and Mutlu, 2023). The use of this biomass is in line with sustainable waste management strategies, as it converts an agricultural byproduct into a beneficial adsorbent while also addressing issues of groundwater contamination (Samimi, 2024; Wang *et al*., 2023). Compared to other biomass sources like sawdust, rice husk, and coconut shell, S. *grandiflora* offers a unique combination of high adsorption efficiency, ease of processing, and renewable biomass production, with a relatively lower lignin content that facilitates easier activation and modification for enhanced adsorption performance (Ratnani *et al*., 2019; Talat *et al*., 2018). Moreover, past studies have highlighted the effectiveness of biomass-based activated carbon in adsorbing fluoride and heavy metals, implying that S. *grandiflora* could be appropriate for similar applications (Niyitegeka *et al*., 2023; Ousman *et al*., 2023; Tefera *et al*., 2020). This study focused on using agriculture-based activated carbon to remove fluoride from groundwater. This task encompassed the preparation of adsorbents, the experimental design, the quantification of adsorption capacity, and the analysis of factors affecting the process through modeling. The main objectives were: i) to prepare activated carbon from S. *grandiflora* wood at various activation temperatures and identify the optimal temperature for maximum surface area and pore volume for fluoride removal; ii) To comprehend the sorption mechanism, the morphology of S. *grandiflora* activated carbon (SGAC) will be analyzed using fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), energy-dispersive x-ray spectroscopy (EDX), and x-ray diffraction (XRD); iii) to conduct batch adsorption studies to determine optimal process parameters (particle size, dosage, agitation speed, contact time) for maximum fluoride removal; iv) to assess maximum adsorption capacity using Freundlich and Langmuir isotherms and determine adsorption kinetics through pseudo-first and second-order models; v) to validate SGAC's fluoride removal efficiency and its effect on other groundwater quality characteristics; and vi) to assess SGAC's ability to regenerate for multiple cycles in order to lower preparation costs. This study was conducted at Kalasalingam Academy of Research and Education (KARE), Tamil Nadu, India, in 2024.

MATERIALS AND METHODS

Materials

Wood from S. *grandiflora*, commonly known as Agathi in Tamil Nadu, was collected in Silamalai, Theni, Tamilnadu, India. The wood measured 15 centimeters (cm) in height and 7.3 cm in average diameter. S. *grandiflora* featured slender branches and a sparse canopy, characterized by deeply

wrinkled, yellowish-brown bark. Cows are fed leaves to produce more milk. Used as a vegetable are the leaves, flowers, and fruit of S. *grandiflora*. High-purity analytical grade chemicals intended for immediate application were sourced from Merck Biopharma in India and employed to analyze various properties of groundwater. Chemical solutions were prepared using double-distilled water to analyze the materials.

Preparation of S. *grandiflora activated carbon*

S. *grandiflora* wood was collected from the local region, cut the wood materials into small pieces, and then dried in the sun for 2 hours (h) to remove surface moisture content. The selection of S. grandiflora's stem for activated carbon production in this study is based on its elevated lignocellulosic content, which contributes to increased carbon yield and porosity, both vital for the adsorption of fluoride. Additionally, its lower extractive content compared to leaves or roots minimizes interference in adsorption efficiency. Evidence from studies suggests that activated carbon obtained from stems has a superior surface area and a variety of functional groups that are beneficial for the fluoride removal. Its structural stability also ensures better regeneration potential, making it a sustainable choice for water treatment applications (Kumar *et al*., 2019). According to earlier studies, the production of activated carbon from wood generally occurs at temperatures between 500 and 1000 degrees Celsius (°C) (Ratnani *et al.,* 2019). This study also obtained the activated carbon from the S. *grandiflora* wood at the temperatures of 500, 550, 600, 650, 700, and 750 °C in 2 h of contact time, of which the study found the maximum pore size and number of pores at 650 °C. The Brunauer-Emmett-Teller (BET) surface area of SGAC was found to be maximum at 650 °C with 1236.3 square meters per gram (m^2/g) and the pore volume corresponding to a surface area is 0.85 cetimeter cubes per gram (cm^3/g)**,** when compared to the surface area of SGAC at other temperatures (which was not shown in this study). This study employed several process parameters to maximize the removal of fluoride from groundwater using SGAC that had been produced at 650 °C. The preparation of activated carbon from S. grandiflora generally involves the removal of its bark, as it contains elevated amounts of extractive compounds that may hinder the effectiveness of adsorption. The mass of the dried plant samples is approximately 430 grams per kilogram (g/kg) of fresh stem material, based on the moisture content at the time of experiment.

Material characterization

i. Fourier transform infrared spectroscopy: FTIR was utilized to know the various functional groups available in SGAC for removing fluoride in groundwater. Once the SGAC powder was finely ground, it was blended with dry potassium bromide (KBr) in a proportion of 2 mg to 200 mg. Using Perkin Elmer Spectrum 100 FTIR spectrophotometry, the sample was scanned across a wavelength (WL) of 400–4000/cm.

ii. Scanning electron microscope: Among the various tools available, the SEM stands out as a highly valuable resource for the examination and analysis of the morphological traits of microstructures. The beam voltage from 500 to 2,000 volt (V), magnifications from 250 to 65,000, and resolution of 3 nanometer (nm) at 1,000 V were used to capture the microphotographs of the prepared SGAC. Different resolutions of SEM images were obtained using FE-SEMs from the ZEISS 200 High-Resolution instrument.

iii. Energy dispersive x-ray: EDX, an elemental analysis method, is utilized to ascertain the specific elements within SGAC and their corresponding atomic percentages. Each component within SGAC possesses a unique atomic structure, allowing for a specific arrangement of peaks in its x-ray spectrum. This spectrum was captured using a two-dimensional VANTEC-500 detector made by BRUKER EDX.

iv. X-ray diffraction: XRD is a technique used to determine the crystalline or amorphous structure of a sample. When an x-ray beam hits an atom of the SGAC, and the angles and intensities of the diffracted beams are measured produce a three-dimensional (3D) electron density map, which illustrates the molecular structure and the locations of atoms within the material. This investigation, XRD data from 0° to 80° were collected using a Bruker D8 ADVANCE ECO instrument with copper (Cu) K-alpha (Kα) radiation (wavelength lambda (λ) = 1.54060 Å) in a coupled Two Theta/Theta mode.

Collection of groundwater sample

Samples of groundwater were obtained from five different locations on the KARE campus in Krishnankoil, using a secure, insulated container. The collected groundwater samples were taken to the

Table 1: Characteristics of groundwater sample collected from the KARE campus

S.N.	Parameters	Observed value	BIS (IS 10500:2012)
1	pH	6.9	6.5-8.5
2	Total dissolved solids, mg/L	426.87±18.05	500
3	Total hardness, mg/L	432.62±14.28	200
4	Calcium, mg/L	98.45±4.68	75
5	Magnesium, mg/L	31.26±2.54	30
6	Sodium, mg/L	195.76±7.89	200
7	Potassium, mg/L	8.66±0.85	12
8	Chloride, mg/L	235.74±8.23	250
9	Sulphate, mg/L	195.84±6.52	200
10	Nitrate, mg/L	38.32±3.05	45
11	Fluoride, mg/L	2.50±0.14	1.0
12	Iron, mg/L	0.67±0.04	0.3

Table 2: Experimental design of different process parameters for the removal of fluoride from groundwater using SGAC

S.N.	Particle size (mm)	Adsorption dose (mg/L)	Agitation speed (rpm)	Contact time (min.)
1	0.425	2	100	60
2	0.600	4	200	80
3	1.180	6	300	100
4	2.360	8	400	120
5	4.750	10	500	140

laboratory and kept in a refrigerator at 5 °C to test the quality of the groundwater. Five of these samples were further analyzed to determine the effectiveness of fluoride removal, as well as to measure other groundwater characteristics such as potential of hydrogen (pH), total dissolved solids (TDS), total hardness (TH), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl_2), sulphate (SO_4), nitrate (NO_3), and iron (Fe). Table 1 displays the average characteristic values of groundwater samples taken from five locations, along with the corresponding BIS standard limits. All selected quality characteristics in the groundwater were determined following the American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF) guidelines (APHA, 2017).

Methods

Sorption experiments

Batch adsorption experiments were used to adsorb fluoride onto SGAC, in order to carry out the adsorption test and evaluate the efficacy of SGAC in fluoride removal from groundwater, 250 milliliters (mL) of a groundwater sample was placed in a magnetic stirrer apparatus. Particle size in millimeter (mm), adsorbent dosage in gram (g), agitation speed in revolutions per minute (rpm), and contact time in minutes (min.) were the chosen process parameters for eliminating fluoride from groundwater against the initial fluoride concentration of 2.5±0.14 mg/L, pH of 6.9, and room temperature of 27 °C. A series of batch studies were performed with various process parameters to determine the best value. Following this, an equilibrium study was executed using the optimal parameters across different contact times until reaching equilibrium contact time. The SGAC and fluoride mixed solution was transferred to the filter unit for filtering using Whatman filter paper No. 41 as the filter media, following the specific contact time of 60 min. in the batch study and different contact times in the equilibrium study, when the SGAC and fluoride adsorbate came into contact with one another. Table 2 outlines the experimental design for various process parameters aimed at the removal of fluoride ions from groundwater utilizing SGAC. The percentage of fluoride removed from groundwater by SGAC was calculated, using Eq. 1 (Durairaj, 2024):

$$\text{Percentage reduction} = \frac{(C_i - C_f)}{C_i} \times 100 \quad (1)$$

Where, C_i represents the fluoride concentration in groundwater (mg/L) before treatment using SGAC and C_f represents the fluoride concentration in

groundwater (mg/L) after treatment using SGAC.

Particle size (Palodkar *et al.,* 2017) was selected based on available sieve sizes, agitation speed (Chandraker *et al.,* 2021) based on the magnetic stirrer range, and adsorption dosage (Iwar and Ugwudike 2022) and contact time (Amaibi *et al.,* 2024) based on prior studies on fluoride removal. SGAC efficacy was assessed by measuring fluoride concentration and other groundwater characteristics in treated water, APHA guidelines (APHA, 2017).

Adsorption isotherms

An isotherm model was used in this study to determine the maximum fluoride removal efficiency of SGAC in groundwater. Utilizing data from the equilibrium study, the model was formulated with an emphasis on the optimal process parameters, including particle size, adsorbent dosage, agitation speed, and contact duration. The equilibrium study was carried out for various contact periods starting from the beginning against all other optimum process parameters. The equilibrium adsorption capacity (q_e) milligrams per gram (mg/g) was calculated using Eq. 2 (Fuentes Gandara *et al.,* 2024). The effectiveness of the Langmuir and Freundlich isotherm models, both of which are frequently employed, was evaluated against equilibrium data to determine their suitability for fluoride removal from groundwater using SGAC. The equations of the Langmuir and Freundlich isotherm models are presented using Eqs. 3 and 4 (Fuentes Gandara *et al.,* 2024):

$$q_e = \left(\frac{C_i - C_e}{m}\right) x\, V \quad (2)$$

The Langmuir isotherm equation is presented as:

$$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m} \quad (3)$$

The Freundlich isotherm equation is given by:

$$\ln q_e = \frac{1}{n}\ln C_e + \ln K_F \quad (4)$$

Where, K_L is the Langmuir isotherm constant liters per milligram (L/mg), K_F is the Freundlich isotherm constant liters per gram (L/g), n is the adsorption intensity constant varied from 0 to 1, C_e is the equilibrium concentration (mg/L) of fluoride in groundwater, q_m is the maximum adsorption capacity (mg/g) of SGAG for the removal fluoride in groundwater, q_e is the equilibrium absorptivity capacity (mg/g) of SGAG for the removal and volume of groundwater treated for this study is in L.

Kinetic model

One adsorbate concentration is considerably higher than the other adsorbate concentration in a pseudo first-order reaction, the overall behavior of the reaction approximates that of a first-order reaction. The pseudo first order kinetic, using Eq. 5 (Samimi *et al.,* 2024):

$$\ln \frac{(q_e - q_t)}{q_e} = -K_1 t \quad (5)$$

Where, q_t and q_e are the amounts of adsorbate adsorbed at any given time, t and at equilibrium, respectively. The $\ln \frac{(q_e - q_t)}{q_e}$ against time (t) plot yields the value of the kinetic rate constant of pseudo first order K_1. The chemical sorption, referred to as, between the adsorbent and adsorbate. The pseudo second order kinetic model provides a comprehensive forecast of the behavior across the full spectrum of adsorption. Under these circumstances, the adsorption rate depends more on the adsorption capacity than the adsorbate concentration. The pseudo second order reaction, using Eq. 6 (Samimi *et al.,* 2024):

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \quad (6)$$

The plot between $1/q_t$ and t will reveal the pseudo second order adsorption process' rate constant K_2.

Analytical statistics

Using Minitab 21, the standard deviation is calculated to measure the dispersion of data points around the mean. The coefficient of determination (R^2) is used in regression analysis to determine how well the independent variable(s) predict the dependent variable, with values closer to 1 indicating a better fit.

RESULTS AND DISCUSSIONS

Characterizing activated carbon, conducting adsorption studies, and performing isotherm analysis are essential components in the treatment of water. Activated carbon is widely used due to its

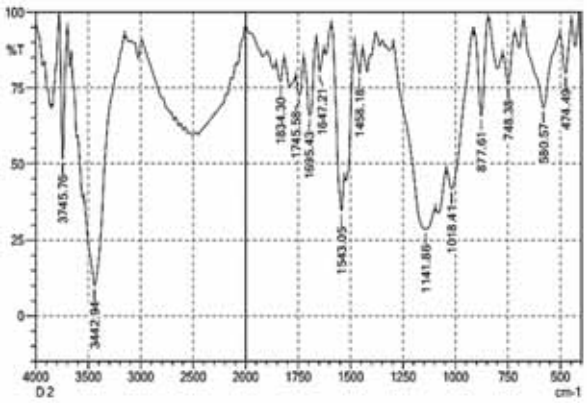


Fig. 1(a)

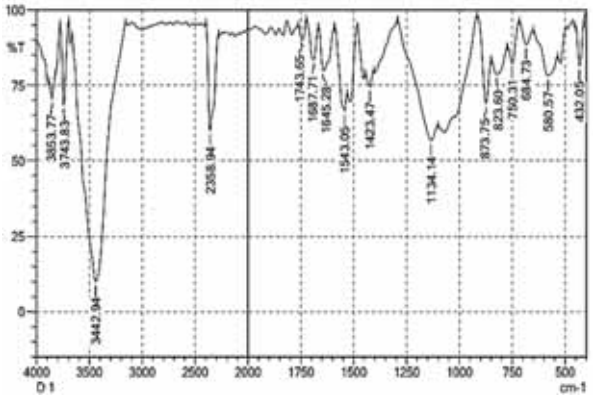


Fig. 1(b)

Fig. 1: FTIR spectrum for SGAC before (1a) and after (1b) removal of fluoride from groundwater

large surface area and porous structure. FTIR, SEM, EDX, and XRD are key for determining the physical and chemical properties of SGAC. The process of adsorption extracts fluoride from groundwater by attaching it to the adsorbent, rendering it a highly effective and affordable method for purification. Isotherm studies help understand SGAC adsorption capacity and behavior, optimizing its use for fluoride removal and improving water purification for safer drinking water.

Characterization of activated carbon

From both structural and chemical viewpoints, the attributes of the materials analyzed in this study correspond with or bolster the findings of other studies. FTIR analysis revealed hydroxyl and carboxyl groups, facilitating fluoride adsorption through electrostatic interactions (Niyitegeka *et al.,* 2023; Palodkar *et al.,* 2017). The characteristics observed in the XRD results revealed a small rise in crystallinity, thereby confirming the presence of additional active sites for fluoride binding (Varol and Mutlu, 2023; Tefera *et al.,* 2020). EDX and SEM characteristics, showing increased oxygen content and a highly porous structure, are consistent with other studies, verifying fluoride uptake and entrapment (Solanki *et al.,* 2021; Zhang *et al.,* 2019; Samimi, 2024; Wang *et al.,* 2023).

Fourier transform infrared spectroscopy

The FTIR spectra of the produced SGAC materials were obtained between 400 and 4000/cm, highlighting structural modifications and the identification of functional groups. Figs. 1a and b, show the FTIR spectra of SGAC before and after fluoride was removed from groundwater, respectively. It can be shown from Fig. 1a that the C=C stretch on SGAC was 1423.47/cm before treatment and moved to 1458.58/cm following groundwater fluoridation (Fig. 1b). After fluoride was removed from groundwater, Nandiyanto *et al.* (2019) found the C=C stretch at a peak value of 1834.30/cm, which reflects the functional group of transition metal carbonyls and five-membered ring anhydrides. The findings revealed C=C stretching at 1637.98/cm with a noticeable increase in the strength of the C=C peak both prior to and following the removal of fluoride from groundwater (Yang *et al.,* 2023). The SGAC spectrum showed consistent peaks before and after treatment at 3442.94/cm, corresponding to O-H stretch and H-bonded vibrations in alcohols and phenols. Peaks at 1734 and 1169/cm were attributed to C-O-C and carbonyl group vibrations. The C-H bent bond vibrations in alkenes were observed at 873.75/cm before fluoride removal from groundwater using SGAC (Fig. 1a). Bakhta *et al.,* (2022) synthesized activated carbon was found to include C=O stretches in the 1500 to 1600/cm range for fluoride removal. The C=O of carboxylate groups was identified at 1543.05/cm. There were variations in peak strength both before and after the fluoride removal process, but the peak range itself remained stable. After treatment with SGAC, these vibrations shifted to 877.61/cm (Fig. 1b). The peak value of 1543.05/cm, falling within the medium N-O symmetric stretch range for nitro chemicals, demonstrated no change pre- and post-treatment.

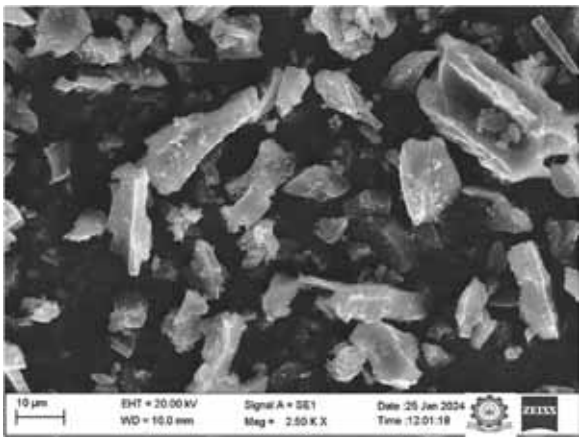


Fig. 2(a)



Fig. 2(b)

Fig. 2: SEM image of SGAC before (2(a)) and after (2(b)) removal of fluoride from groundwater

The decomposition of hemicellulose in S. *grandiflora* produces volatile matter, which may be responsible for the O-H stretching observed in SGAC (Varol and Mutlu 2023).

Scanning electron microscopy

The surface morphology of the activated carbon was examined using SEM, with images taken at a magnification of 1,200 times using the ZEISS 200 High-Resolution FE-SEM instrument. The SEM pictures of SGAC used to remove fluoride from groundwater are displayed in Figs. 2a and 2b. Prior to treatment, SGAC displayed an increased quantity of pores, which was corroborated by the darker coloration seen in the SEM image (Fig. 2a). After fluoride was removed from groundwater, SGAC showed less black colour in an SEM image, indicating the presence of more fluoride on SGAC (Fig. 2b). It is observed from Figs. 2a and 2b that the carbon matrix of SGAC before and after treatment, with the white areas representing the solid surface. The clear distinction observed in the two images implies that fluoride adsorption during the treatment has resulted in a reduction of the pore area. The higher surface area observed in Fig. 2a suggests more active sites for fluoride ions, with areas of higher surface energy being more reactive. The surface in Fig. 2b appears smoother, affecting the chemical bonds and interactions between SGAC and fluoride ions (Chandraker *et al.,* (2021).

Energy-dispersive x-ray spectroscopy

The EDX technique was employed to analyze the elemental composition and chemical properties of the sample. The untreated and fluoride-treated samples had higher concentrations of carbon and oxygen ions than other ions, according to the EDX elemental analysis. Different ratios for the Na, Mg, Aluminum (Al), Phosphorus (P), Sulphur (S), Chlorine (Cl), K, and Ca were also seen in the treated and untreated samples. Table 3 presents the EDX results for SGAC both prior to and following the extraction of fluoride from groundwater.

Table 3 shows the absence of P and S in SGAC after fluoride removal, likely due to the formation of P trifluoride and sulphur hexafluoride. The elemental weight percentage of carbon, oxygen, Na, and Cl_2 increased, likely because elements like Al and Ca precipitate and are removed, raising the relative concentration of remaining soluble elements. Following SGAC treatment, the elemental weights of Al, K, and Ca were reduced due to the development of insoluble fluoride compounds, with K experiencing a comparatively minor decrease. Mg content remained stable as SGAC did not interact significantly with Mg ions. An increase in fluoride signal strength was observed in the treated samples, implying that fluoride ions might be displacing oxygen-containing ions (OH^-) on the adsorbent surfaces.

X-ray diffraction

X-ray radiation spectra can help identify whether the adsorbent possesses a crystalline or amorphous structure. Figs. 3a and 3b, respectively, display the peak values obtained from the XRD on SGAC for the removal of fluoride from groundwater. WL used for the XRD experiment was 1.54060 angstrom (Å).

Table 3: EDX for SGAC before and after removal of fluoride from groundwater

Element	CK	OK	NaK	MgK	AlK	PK	SK	ClK	KK	CaK
Before treatment with SGAC										
Weight percent (%)	78.3	16.5	0.6	0.5	0.4	0.4	0.2	0.3	1.3	1.6
After treatment with SGAC										
Weight %	78.8	17.1	2.1	0.5	0.3	-	-	0.6	0.3	0.3

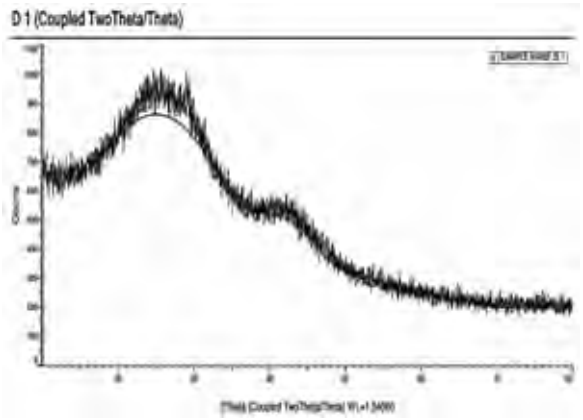


Fig. 3(a)

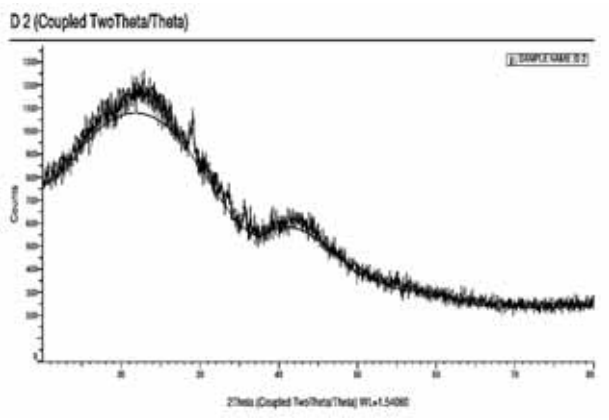


Fig. 3(b)

Fig. 3: XRD image of for SGAC before (3(a)) and after (3(b)) removal of fluoride from groundwater

Before treatment, the XRD pattern of SGAC shows four separate peaks at different 2 teta (θ) angles: Peak 1 has a 2θ angle of 17.561°, Peak 2 has a 29.561° angle, and Peak 3 has a 25.628° angle (Fig. 3a). The presence of Peaks 1 and 2 implies the likelihood of more distantly spaced diffraction peaks, which could signify the existence of several phases with similar lattice properties or a phase characterized by a significant degree of crystallinity. Peak 2 at 2θ = 29.061° in Fig. 3b may reflect a new lattice plane or crystallographic phase, or it may suggest a distinct crystalline structure or orientation in the material. At 2θ = 35.628°, there appears to be another separate diffraction peak, potentially associated with a different crystalline phase or lattice plane (Fig. 3b).

The XRD pattern shows that before treatment, 17.2% of the SGAC structure is crystalline, while 82.8% is amorphous (Fig. 3a). Fluoride removal resulted in a slight increase in crystalline content by 0.2%, and a corresponding decrease in amorphous content by 0.2% (Fig. 3b). The crystallinity rose slightly from 17.2% to 17.4%, and the amorphous content decreased from 82.8% to 82.6%. These slight modifications suggest that the adsorption of fluoride had a minimal effect on the overall structure of SGAC. The resilience of both crystalline and amorphous components implies that the adsorption process does not undermine the structural integrity of SGAC, highlighting its capability for several recycling cycles without notable loss of quality. The enhanced fluoride removal efficiency of *Sesbania grandiflora* activated carbon is attributed to its structural and chemical characteristics, as confirmed by FTIR, XRD, EDX, and SEM analyses. The identification of hydroxyl and carboxyl functional groups through FTIR indicates their role in promoting fluoride adsorption through both electrostatic interactions and ligand exchange mechanisms (Niyitegeka *et al*., 2023; Palodkar *et al*., 2017). XRD revealed a predominantly amorphous structure with a slight crystallinity increase (17.2% to 17.4%) post-adsorption, ensuring more active sites for fluoride binding (Varol and Mutlu, 2023; Tefera *et al*., 2020). After treatment, EDX results indicated a rise in oxygen levels from 16.5% to 17.1% and detected sodium at 2.1%, which points to the processes of ion exchange and fluoride uptake (Solanki *et al*., 2021; Zhang *et al*., 2019). SEM confirmed a highly porous structure as 0.5–5 micrometers (μm) pore size, with surface smoothing post-adsorption, verifying fluoride entrapment (Samimi, 2024; Wang *et al*., 2023). The

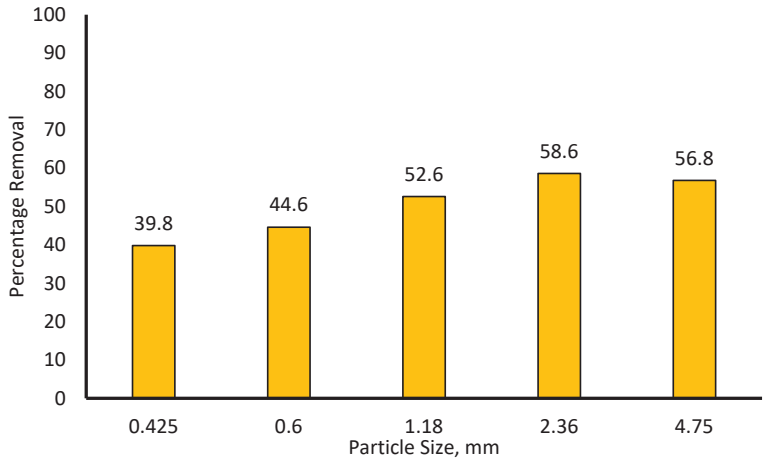


Fig. 4: Removal of fluoride from groundwater using SGAC for various particle size

combination of these features boosts adsorption efficiency, stability, and reusability, establishing Sesbania grandiflora as a viable and eco-friendly option for defluoridation material.

Adsorption study of SGAC

Wood-activated carbon, derived from biomass, is an effective adsorbent for pollutants in water and wastewater due to its high surface area, porosity, and renewability. This sustainable adsorbent aids in water purification and waste reduction, making it an excellent choice for locations with a surplus of wood waste. This study examined the impact of factors such as particle size, adsorbent dosage, agitation speed, and contact time on fluoride adsorption from groundwater by SGAC. This study did not concentrate on the effects of pH and temperature, as modifying pH could result in chemical contamination, and heating groundwater for public use is not a practical solution. Given that groundwater is frequently utilized for household needs, it is crucial to ensure it is treated to minimize contamination.

Effect of particle size

Fig. 4 shows fluoride removal from groundwater using SGAC at particle sizes ranging from 0.425 to 4.750 mm. Fluoride reduction was quantified with a 2 g dosage of adsorbent, an agitation speed set at 100 rpm, and a contact duration of 60 minutes. Results indicated that fluoride removal increased as particle size grew, with maximum sorption achieved at 2.360 mm. No significant difference was observed between the particle sizes of 2.360 mm and 4.750 mm. The maximum fluoride removal percentages were 39.8, 44.6, 52.6, 58.6, and 56.8% for particle sizes of 0.425, 0.600, 1.180, 2.360, and 4.750 mm, respectively. Consequently, the optimal particle size for achieving the highest fluoride removal, which is 58.6%, was found to be 2.360 mm. Wang *et al.* (2023) developed an Fe-La composite adsorbent with a specific surface area of 1113.13 m^2/g for simultaneous phosphate and fluoride removal using a one-pot hydrothermal technique. Wang *et al.* (2023) showed that the highest fluoride removal was achieved with SGAC, which had a surface area of 1236.3 m^2/g. Adsorbents that feature smaller pore sizes and a limited range of pore sizes present a wealth of active adsorption sites along with a high surface area-to-volume ratio. Nonetheless, this can restrict the adsorption of larger fluoride ions, which may lead to a decrease in their overall effectiveness (Kumari *et al.,* 2019).

Effect of dosages

Fig. 5 shows experimental results obtained by varying SGAC dosages between 2, 4, 6, 8, and 10 g for fluoride reduction in groundwater, with optimal conditions of a particle size of 2.360 mm, agitation speed of 100 rpm, 60 min. contact time, an initial fluoride concentration of 2.5 ± 0.14 mg/L, pH of 6.6, and a temperature of 27 °C. The data suggests that at lower dosages, fluoride removal was minimal, whereas it became more effective as the dosage increased. SGAC enhanced fluoride sorption up to an 8 g dosage, and at 10 g, the removal percentage resembled that of the 8 g dosage. The maximum fluoride removal percentages were 58.6, 66.2, 72.1,

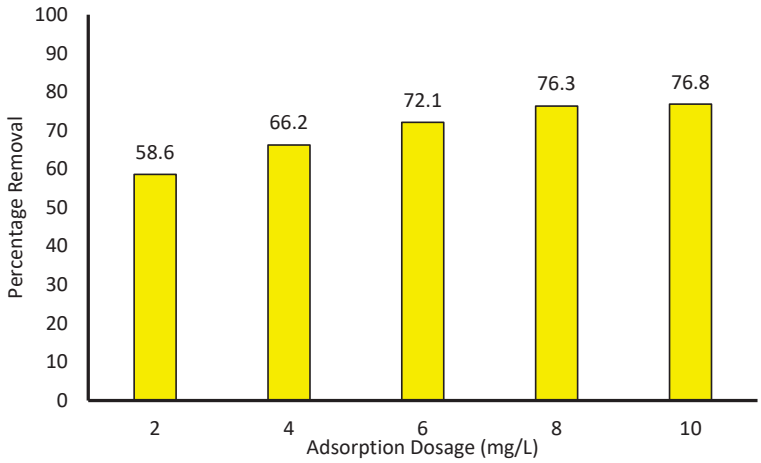


Fig. 5: Removal of fluoride from groundwater using SGAC for various adsorbent dosage

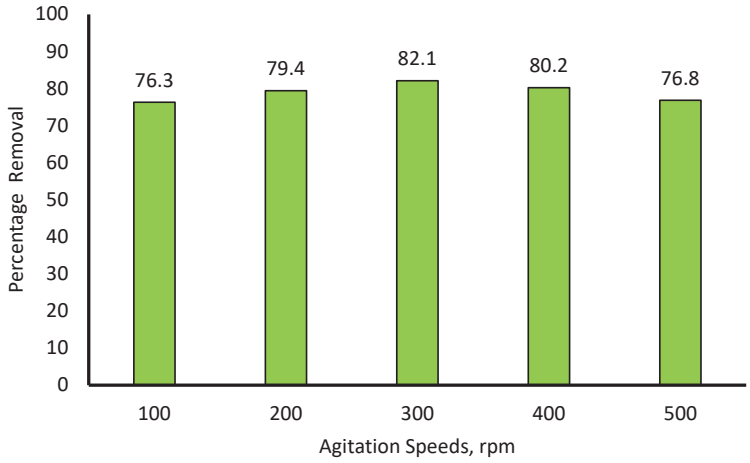


Fig. 6: Removal of fluoride from groundwater using SGAC for various agitation speed

76.3, and 76.8% for dosages of 2, 4, 6, 8, and 10 g, respectively, with the optimal dosage identified as 8 g, achieving a removal of 76.3%. Lower fluoride removal at smaller dosages was due to fewer active binding sites, and higher dosages led to site aggregation, reducing adsorption efficiency (Bhaumik and Mondal, 2016). Hu *et al.* (2018) and Kumari *et al.* (2019) also observed that adsorption increased with higher adsorbent masses. Aligned with these findings, the study indicated that the effectiveness of fluoride removal enhanced with SGAC dosage up to 8 g, but no significant differences were noted beyond that point. As reported by de Carvalho Costa *et al.* (2024), the most effective dosage for the removal of fluoride is 8 g.

Effect of agitation speed

Fig. 6 illustrates fluoride removal from groundwater using SGAC at agitation speeds ranging from 100 to 500 rpm, increasing in 100 rpm increments. The assessment of fluoride concentration reduction was conducted using an ideal particle size of 2.360 mm, a dosage of 8 g, and a contact duration of 60 min. Fluoride removal was minimal at 100 rpm but increased with speed, reaching a maximum of 82.1% at 300 rpm. However, at 400 and 500 rpm, removal efficiency declined due to reduced SGAC-fluoride contact. The maximum fluoride removal percentages at 100, 200, 300, 400, and 500 rpm were 76.3, 79.4, 82.1, 80.2, and 76.8%, respectively. Thus, 300 rpm was identified as the optimal agitation speed for

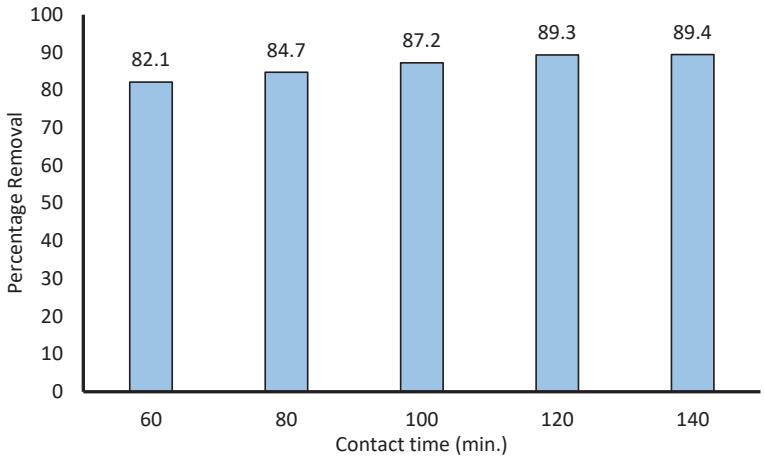


Fig. 7: Removal of fluoride from groundwater using SGAC for various contact time

fluoride removal using SGAC. Due to the agitation speed, fluoride demonstrated improved adhesion to the SGAC surface, which is consistent with the results reported by Iwar *et al.* (2021). The adsorption rate and fluoride ion absorption capacity decreased beyond 650 rpm agitation speed because there was a greater space between the fluoride ions and the adsorbent surface (Bhaumik and Mondal 2016). Conversely, the results of this study utilizing SGAC aligned with the findings of Bhaumik and Mondal (2016), although the agitation speed exceeded 300 rpm. The variations observed in current study compared to previous studies are attributed to the specific properties of the activated carbon chosen for the extraction of fluoride from groundwater.

Effect of contact time

Fig. 7 illustrates the effect of contact time on fluoride removal using SGAC, with durations ranging from 60 to 140 min in 20 min increments. The experiment was conducted at an optimal particle size of 2.360 mm, an 8 g dosage, and an agitation speed of 300 rpm. At the 60 min interval, the fluoride removal efficiency was relatively low; however, it increased with time, achieving its highest level at 120 min. Beyond this duration, no significant gains were noted at 140 min, suggesting that SGAC had fully utilized its fluoride sorption capacity by 120 min. The maximum removal percentages were 82.1, 84.7, 87.2, 89.3, and 89.4% for 60, 80, 100, 120, and 140 min, respectively. Therefore, 120 min was identified as the optimal contact time, achieving 89.3% fluoride removal. The current findings are in agreement with prior studies, notably those by Talat *et al*. (2018), who demonstrated an 86% fluoride removal rate after 60 min using activated carbon sourced from coconut husks at a pH of 5, with an initial fluoride concentration of 10 mg/L. Similarly, Tefera *et al.* (2020) observed 86% fluoride removal at 60 min using avocado seed-derived activated carbon at pH 6. Bonyadi *et al.* (2019) demonstrated that 100 min with *Populusalba* activated carbon (PAC) resulted in 93.37% fluoride removal at 10 mg/L fluoride concentration. The determination of 120 min as the most effective contact time in this study yields significant insights for upcoming groundwater treatment strategies, boosting fluoride removal effectiveness through the use of SGAC.

In this study, the influence of individual factors—namely particle size, dosage, agitation speed, and contact time on the removal of fluoride was analyzed, with all other parameters held constant at their ideal settings. Experimental investigations were conducted to optimize fluoride removal efficiency, determining the ideal conditions as 2.360 mm particle size, 8 g dosage, 300 rpm agitation speed, and 120 min contact time, achieving a maximum fluoride removal of 89.3%. Of all the characteristics examined, agitation speed and contact time were determined to significantly affect adsorption, as they directly improve the interaction between the adsorbent and fluoride ions, leading to increased removal efficiency. The greater removal values observed with optimal contact time (Fig. 7) and

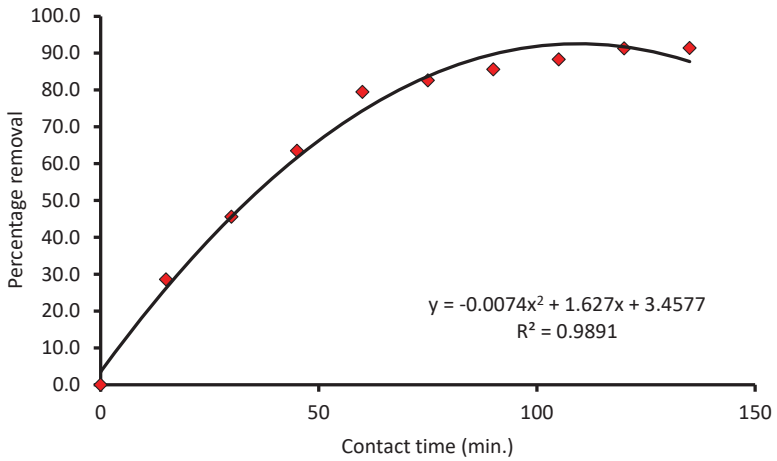


Fig. 8: Removal of fluoride in groundwater using SGAC for the optimum equilibrium data

agitation speed (Fig. 6) compared to the material itself (Figs. 4 and 5) are primarily due to enhanced mass transfer and increased interaction between the adsorbent and adsorbate. Extended contact time enables a greater number of fluoride ions to engage with the active sites on the adsorbent, facilitating equilibrium and enhancing the adsorption capacity. Likewise, elevating the agitation speed improves the distribution of the adsorbent in the solution, thereby minimizing boundary layer resistance and promoting a more uniform engagement between fluoride ions and active sites on the adsorbent surface. In contrast, factors like particle size and adsorbent dosage, while important, may not provide the same level of interaction or mass transfer efficiency, hence their lower impact on removal efficiency compared to contact time and agitation speed.

Equilibrium study

Fig. 8 shows equilibrium study results on the removal of fluoride from groundwater using SGAC for various contact times between 0 and 140 min with an increment of 20 min. The observed percentage decrease in fluoride ion concentration in groundwater occurred at an optimal particle size of 2.360 mm, a dosage of 8 g, and an agitation speed of 300 rpm, evaluated over various contact times. The initial fluoride concentration was 2.5±0.14 mg/L, with a pH of 6.9 and temperature of 27 °C. The findings showed that SGAC removed a small proportion of fluoride at shorter contact times, with removal increasing up to 120 min. Beyond this, no significant difference was observed at 140 min, indicating maximum removal was achieved at 120 min. Fig. 8 also shows that nearly 80% of fluoride removal occurred within the first 100 min. The findings from the equilibrium studies were applied to adjust isotherm and kinetic models, which helped in identifying the maximum adsorption capacity and the rate of fluoride removal by SGAC.

Adsorption isotherms

The adsorption isotherm serves as an essential instrument for demonstrating the sorption capacity of an adsorbent and the underlying mechanisms of the adsorption process. It evaluates the relationship between the amount of fluoride adsorbed at the solid/solution interface and the fluoride concentration remaining in the bulk solution. The equilibrium data collected under ideal conditions through SGAC were analyzed using Freundlich and Langmuir adsorption isotherms to assess fluoride removal from groundwater. Fig. 9(a) presents the Langmuir isotherm model for SGAC, where the K_L value was 3.5982, and the maximum adsorption capacity (q_m), determined by fitting experimental data to linear Langmuir equations, was 0.318 mg/g. The R^2 of 0.9121 indicates that fluoride adsorption was generally favorable. The separation factor (R_L), which determines adsorption type and feasibility, ranges from 0 to 1, confirming a favorable adsorption isotherm. Further analysis of SGAC's effectiveness was conducted using the Freundlich isotherm, which suggests that multilayer adsorption takes place on a heterogeneous adsorbent with adsorption sites

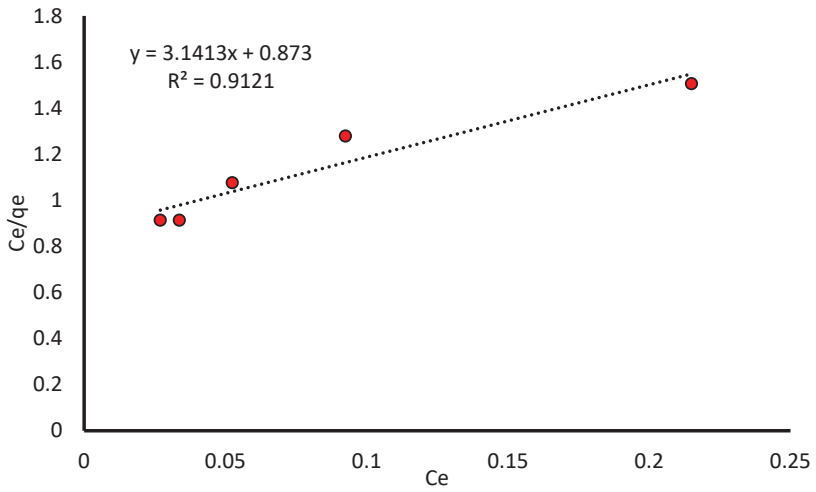


Fig. 9(a)

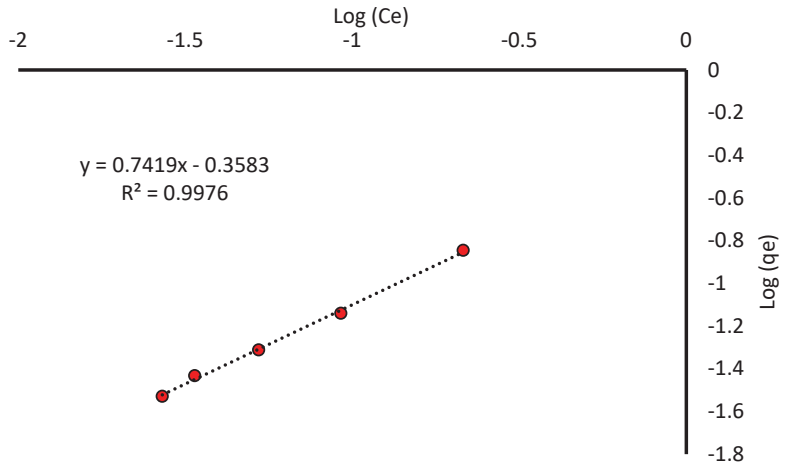


Fig. 9(b)

Fig. 9: Longmuir (9(a)) and Freundlich (9(b)) isotherms for the removal of Fluoride from groundwater using SGAC

that possess varying energy. Fig. 9(b) illustrates the Freundlich isotherm for fluoride removal, showing an R^2 value of 0.9976, with 1/n and K_F values of 0.7419 and 0.6988, respectively. Since 1/n is less than 1, it suggests chemical adsorption rather than a linear process. Comparing Figs. 9(a) and 9(b), the Freundlich isotherm had a significantly higher R^2 value than the Langmuir model, indicating that SGAC exhibits multilayer heterogeneous adsorption, which governs fluoride removal from groundwater.

This study found that the Freundlich isotherm model fits better than the Langmuir model for fluoride removal from groundwater using SGAC due to the heterogeneous nature of the adsorbent surface and the multilayer adsorption process. The Freundlich model is well-suited for illustrating adsorption on surfaces that have varying affinities for fluoride ions, reflecting the highly porous and amorphous structure of SGAC, which includes multiple active sites with distinct energy characteristics (Senewirathna *et al*., 2022). Unlike the Langmuir model, which assumes a uniform surface with a monolayer of adsorbate, the Freundlich model accommodates the complex interaction between fluoride ions and various functional groups on SGAC, such as hydroxyl and carboxyl groups, resulting in both physical and

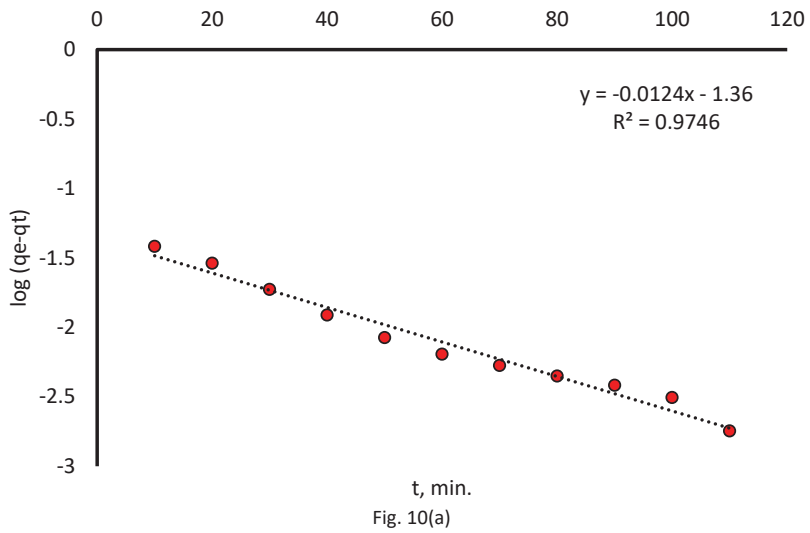


Fig. 10(a)

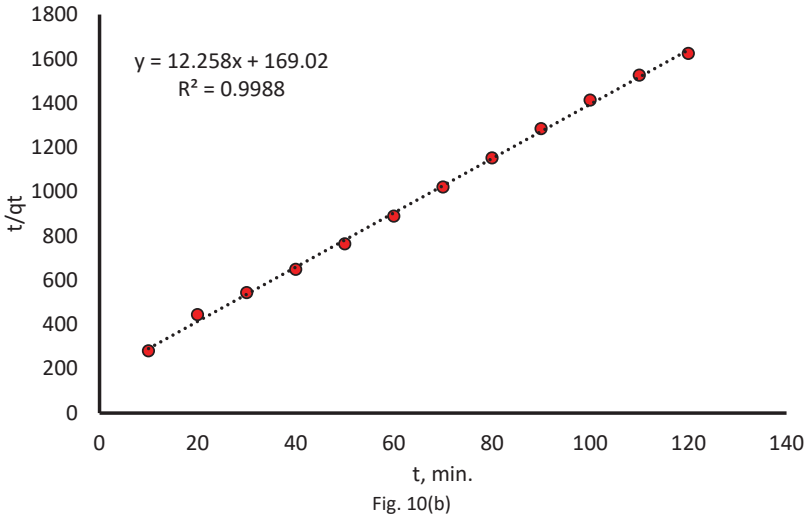


Fig. 10(b)

Fig. 10: Pseudo first order (10(a)) and Pseudo second order (10(b)) kinetic models for the removal of Fluoride from groundwater using SGAC

chemisorptive bonding (Niyitegeka *et al*., 2023). Furthermore, the Freundlich model provides a more precise depiction of SGAC's continuous adsorption capacity, since the fluoride removal does not abruptly level off, facilitating adsorption through multiple phases (Ousman *et al*., 2023). Consequently, the Freundlich isotherm more accurately represents the fluoride adsorption behavior on SGAC, which involves a non-ideal, heterogeneous process rather than the uniform adsorption assumed by the Langmuir model (Solanki *et al*., 2021).

Kinetic study of adsorption

Time-sensitive analyses were undertaken to identify the step that governs the rate and to elucidate the adsorption mechanism. In this study, fluoride removal was tested against optimal process parameters such as particle size, adsorption dosage, agitation speed, contact time, and initial concentration. To determine the equilibrium time for fluoride removal from groundwater using SGAC, the kinetics of adsorption were analyzed. The maximum removal in the first 60 min was due to fluoride adsorption onto the active surface and greater pore availability on SGAC (Fig. 10(a)). The removal percentage decreased as contact time progressed from 60 min, reaching equilibrium at 120 min with maximum fluoride removal of 91.5%. To ascertain the adsorption mechanism for

fluoride removal with SGAC, the equilibrium data was fitted using two models: pseudo first order and pseudo second order. The experimental data were analyzed using both linear representations of the pseudo first-order and pseudo second-order kinetic models. Figs. 10(a) and 10(b) show the pseudo first order and pseudo second order kinetic models, respectively. The R^2 values obtained from the pseudo second order model (0.9988) were greater than those from the pseudo first order model (0.9746) for fluoride removal using SGAC. Notably, there was a stronger correlation (0.08157 mg/g) between the experimental and computed q_e values for the pseudo second order model than for the pseudo first order model (0.04365 mg/g). Additionally, the constants K_1 and K_2 were found to be 0.0124 and 0.8886, respectively, indicating that the pseudo second order model had a greater rate constant than the pseudo first order model.

Fito *et al.* (2019) found the Freundlich isotherm (R^2 = 0.98) best fitted experimental data for *Catha edulis* stem activated carbon at room temperature, pH 2, 1.5 g in 100 mL, and an initial fluoride concentration of 30 mg/L, indicating a multilayer adsorption process. Tefera *et al.* (2020) determined the Langmuir model fitted experimental data well, with a maximum adsorption capacity of 1.2 mg/g. Bakhta *et al.* (2022) confirmed similar results using activated carbon for fluoride removal. The study conducted by Al-Musawi *et al*. (2024) on magnetized hazelnut shell activated carbon revealed that the pseudo-second-order kinetic model was particularly revealing, with the kinetic process being governed by intra-particle and liquid film diffusion mechanism. The Langmuir model fit the data well, with a monolayer adsorption capacity of 0.3065 mg/g and R^2 = 0.93 (Niyitegeka *et al.*, 2023). Amaibi *et al.* (2024) found the Langmuir isotherm (maximum adsorption capacity of 0.02 mg/g, R^2 = 0.992) best fitted data for lemon peel activated carbon. This study determined that the rate and capacity of adsorption on activated carbon are influenced by surface area, pore architecture, and the presence of active functional groups on the surfaces. Furthermore, raw materials, such as wood, coconut shell, or coal, impact surface chemistry and porosity, affecting adsorption behavior. It is vital to comprehend these factors in order to modify the characteristics of activated carbon for better fluoride removal, underscoring the necessity for detailed characterization and tailored solutions for specific water treatment applications.

Verification of experimentation

The percentage removal of fluoride from groundwater also affects the other parameter concentration in groundwater. This study examined the changes in the concentration of various parameters in groundwater through the use of SGAC, as well as the effectiveness of fluoride removal from groundwater. The maximum removal efficiency of other water quality characteristics was assessed at the optimum particle size of 2.36 mm, adsorption dosage of 8 g, agitation speed of 300 rpm, and contact time of 120 min. In Table 4, the maximum percentage of fluoride removal, along with other groundwater quality characteristics, is displayed for SGAC, with the exception of pH. The pH was improved from 6.9 to 7.4 after treatment with SGAC, which showed that it was within the standard limit as prescribed by the BIS standard.

From Table 4, it may be noted that maximum removal percentages of TDS, TH, Ca, Mg, Na, K, Cl_2, SO_4, NO_3, F, and Fe were found to be 77.20 ± 0.8, 73.80 ± 0.5, 81.90 ± 0.5, 84.10 ± 0.8, 71.90 ± 0.7, 81.60 ± 0.6, 74.90 ± 0.3, 82.50 ± 0.2, 79.80 ± 0.9, 89.30 ± 0.4, and 89.70 ± 0.7 respectively. After the treatment of groundwater with SGAC, the value of all quality characteristics was below the standard limit of BIS. The findings from the validation test suggest that the most effective conditions for fluoride removal from groundwater involve a particle size of 2.36 mm, an adsorption dosage of 8 g, an agitation speed of 300 rpm, and a contact time of 120 min. Additionally, these parameters enhanced all aspects when SGAC was applied at a pH value of 7.4.

Regeneration test

This study ultimately focuses on understanding how expended SGAC can be reused. The regeneration capacity of SGAC for the removal of fluoride was evaluated using 0.1 mole (mol) sodium hydroxide (NaOH) (Tan *et al.*, 2020). The desorption procedure began by combining 25 mL of 0.1 mol NaOH with saturated fluoride in SGAC and letting the mixture sit for 90 min. The percentage of material removed from the SGAC in the first cycle was 89.5%, while the percentages in the second, third, fourth, and fifth cycles were 87.3, 85.4, 82.1, and 78.3%, respectively.

Table 4: Percentage removal of all quality characteristics in groundwater using SGAC

S.N.	Parameters	Initial Value* (A)	Final Value+ (B)	Removal Value# (C)	Removal Percentage^ (D)
1	Total dissolved solids, mg/L	426.87	97.33	329.54	77.20±0.8
2	Total hardness, mg/L	432.62	113.35	319.27	73.80±0.5
3	Calcium, mg/L	98.45	17.82	80.63	81.90±0.5
4	Magnesium, mg/L	31.26	4.97	26.29	84.10±0.8
5	Sodium, mg/L	195.76	55.01	140.75	71.90±0.7
6	Potassium, mg/L	8.66	1.59	7.07	81.60±0.6
7	Chloride, mg/L	235.74	59.17	176.57	74.90±0.3
8	Sulphate, mg/L	195.84	34.27	161.57	82.50±0.2
9	Nitrate, mg/L	38.32	7.74	30.58	79.80±0.9
10	Fluoride, mg/L	2.50	0.27	2.23	89.30±0.4
11	Iron, mg/L	0.67	0.07	0.60	89.70±0.7

*Initial Value (A) = Initial concentration of all parameters value in groundwater before treatment using SGAC
+Final Value (B) = Initial concentration of all parameters value in groundwater before treatment using SGAC
#Removal Value(C) = A – B
^Removal Percentage (D) = (C/A) x 100
Note: The average value is presented in columns A, B, and C, and the average percentage removal with the standard error (SE) of the mean is presented in column D for all parameters

With an increase in the number of cycles, the efficiency of desorption decreased. Because the previously adsorbed fluoride in SGAC could not be eliminated during the desorption process, there was a decrease in regeneration. The interaction of fluoride with various functional groups in SGAC plays a significant role in reducing its reusability. The ability of SGAC to be utilized five times for the extraction of fluoride from groundwater indicates that the material demonstrated strong stability throughout the desorption process (Vardhan and Srimurali, 2016). SGAC exhibited good stability for reusability, as evidenced by the fifth cycle desorb of the fluoride concentration of 3.526 mg/L from the absorbed fluoride in SGAC (which was more than the desorbed concentration of 3.526 mg/L). The preparation cost of SGAC decreased fivefold due to its repeated use in removing fluoride from groundwater on five occasions (Zhang *et al.,* 2019). Consequently, the SGAC that is produced can be used effectively to lower the concentration of various water quality parameters in both water and wastewater contexts, as well as to reduce fluoride levels in groundwater.

Enhanced fluoride removal comparison study

Fluoride contamination in groundwater poses health risks, prompting research on activated carbon-based adsorbents. The findings of this study underscore SGAC as a viable, sustainable, and cost-efficient alternative, characterized by enhanced conditions and effective adsorption dynamics. Table 5 compares activated carbon adsorbents from various plant sources. *Cocos nucifera*-based carbon achieved 94.4% fluoride removal (Palodkar *et al.,* 2017), while SGAC reached 89.3% without extensive pore modifications. *Ficus benghalensis*-based adsorbent removed 90% fluoride (George and Tembhurkar, 2018), but SGAC exhibited superior adsorption (R^2 = 0.9976). *Catha edulis* carbon achieved 73% removal at pH 2 (Fito *et al.,* 2019), whereas SGAC reached 89.3% at pH 7.4 with lower dosage, making it a practical solution for large-scale water treatment. In contrast to earlier studies, the current study, reveals that SGAC is capable of attaining similar or greater fluoride removal rates under conditions that are both more practical and cost-effective. Chandraker *et al.* (2021) achieved 92% fluoride removal using sugarcane bagasse-based carbon, while the present study attained 89.3% with a larger particle size (2.360 mm), reducing the need for extensive refinement. According to Chukka *et al*. (2022), the optimization of coconut shell carbon resulted in a 69.5% removal rate. However, SGAC outperformed this by achieving an 89.3% removal rate, highlighting its enhanced effectiveness for drinking water purification. Iwar and Ugwudike (2022) achieved 99.1% fluoride removal with 2.0 mg/g adsorption capacity using response surface methodology (RSM) at 298 K and pH 5, the

Table 5: Comparison of fluoride removal efficiency using various activated carbon adsorbents in different water types

S.N.	Activated carbon	Types of Water	Botanical Name	Removal Percentage	Characterisation	Duration	Sources
1	Coconut	wastewater	*Cocosnucifera*	Removal efficiency of 94.4%	Activated carbon dose = 2 g, pH = 2 Initial fluoride concentration = 2 mg/L Temperature = 303 K (30°C) Agitation speed = 150 rpm	50 min.	Palodkar *et al.*, 2017
2	Banyan tree leaf	water	*Ficusbenghalensis*	Removal efficiency of 97.0%	Adsorbent dosage = 8 g/L Temperature = 26 °C Adsorption capacity = 2.242 mg/g	90 min.	George *et al.*, 2018
3	Khat	Aqueous solution	*Catha edulis*	Removal efficiency of 73.0%	Adsorbent dose = 1.5 g/100 mL, pH= 2 Initial fluoride concentration = 30 mg/L	60 min.	Fito *et al.*, 2019
4	Bagasse	Drinking Water	*Saccharum officinarum*	Removal efficiency of 82.4%	Adsorbent dosage = 4 g/L, pH=4 Temperature = 26°C Particle Size = 0.225 mm Speed = 100 rpm	24 min.	Chandraker *et al.*, 2021
5	Coconut shell	Groundwater	*Cocosnucifera*	Removal efficiency of 69.5%	Initial fluoride concentration= 50 mg/L Adsorbent concentration = 1 g/100 mL	60 min.	Chukka *et al.*, 2022
6	Palm shell	Groundwater	*Arecaceae*	Removal efficiency of 99.1%	Adsorbent dosage = 2.0 g/L, pH= 5.9 Speed = 250 rpm Initial fluoride concentration = 4.0 mg/L	120 min.	Iwar and Ugwudike, 2022
7	Lemon peels	Drinking water	*Citrus × limon*	Removal efficiency of 94.9%	Adsorbent dosage = 2.5 g/L, pH=7 Speed = 200 Adsorption capacity = 0.02 mg/g Initial fluoride concentration = 1.0 mg/L	100 min.	Amaibi *et al.*, 2024
8	Agathi plant	Groundwater	S. *grandiflora*	Removal efficiency of 86.3%	Adsorbent dose = 8 g, pH = 6.5, Agitation speed = 300 rpm Particle size = 2.36 mm, Initial fluoride concentration = 2.5 mg/L	120 min.	Current Study

Langmuir isotherm had a maximum adsorption capacity of 146.2 mg/g, while SGAC reached 89.3% at a near-neutral pH with a moderate 8 g/L dosage, indicating greater scalability and economic feasibility. Amaibi *et al.* (2024) reported 97.09% fluoride removal using lemon peel carbon within 100 min, slightly higher than SGAC (89.3%), but SGAC exhibited superior reusability and stability, with minimal crystallinity changes (17.2% to 17.4%) and strong adsorption kinetics. In contrast to these studies, SGAC offers a combination of high removal efficiency and improved operational feasibility, positioning it as a practical and sustainable option for water treatment. Compared to previous study results, this study found that SGAC demonstrated efficient fluoride removal (89.3%) under optimized conditions (2.360 mm particle size, 8 g dosage, 300 rpm agitation, and 120 min contact time), ensuring groundwater quality met BIS standards. Structural analysis confirmed fluoride adsorption through FTIR, SEM, elemental variations (EDX), and stable amorphous nature with minimal crystallinity change (XRD). Adsorption followed the Freundlich isotherm (R^2 = 0.9976), indicating multilayer heterogeneous adsorption, while kinetic analysis confirmed chemisorption as the dominant mechanism (pseudo-second-order model, R^2 = 0.9988). In contrast to earlier studies that relied on harsh chemical methods, SGAC demonstrated high efficiency in practical and environmentally friendly conditions, positioning it as a cost-effective, reusable, and scalable option for large-scale fluoride remediation.

Future research directions

The objective of research should be to improve regeneration processes by investigating alternative solvents or cutting-edge techniques that facilitate fluoride recovery and the restoration of SGAC's adsorption capacity following multiple cycles. Pilot-scale trials in various water matrices, with different contamination levels, are essential to assess SGAC performance in real-world applications. These trials will provide insights into SGAC's behavior under diverse environmental conditions and validate its field applicability. Ongoing long-term investigations into SGAC's influence on human health, environmental factors, and its performance across different regions will confirm its safety and scalability.

Practical implications

SGAC presents a promising material for large-scale defluoridation of groundwater, given its cost-effectiveness, stability, and reusability. Improving production and regeneration processes, as well as incorporating SGAC into hybrid systems, will promote sustainability in the removal of fluoride. SGAC's ability to meet drinking water standards makes it a suitable candidate for widespread use in areas with fluoride contamination. The possibility of extensive application provides major enhancements in public health by confronting water pollution issues on a global scale.

CONCLUSION

The findings of the current study clearly indicate that SGAC is a stable and effective material for adsorbing fluoride from groundwater. Initially, SGAC was characterized using FTIR, SEM, EDX, and XRD to analyze its structural, morphological, and elemental composition before and after fluoride adsorption. FTIR analysis identified functional groups such as C=C, C=O, and O-H, which remained present post-adsorption, with peak shifts indicating fluoride binding. SEM images indicated that the SGAC exhibited a highly porous structure prior to adsorption, which transformed into a smoother and denser form following fluoride absorption. According to the EDX analysis, there was a decline in phosphorus and sulfur, while the rise in carbon, oxygen, sodium, and chloride pointed to mechanisms of precipitation and ion exchange. XRD analysis confirmed that SGAC remained amorphous, with a minor increase in crystallinity (from 17.2% to 17.4%), ensuring structural stability. Investigative experiments were undertaken to refine the fluoride removal process, pinpointing the optimal parameters as a particle size of 2.360 mm, an 8 g dosage, a stirring speed of 300 rpm, and a contact time of 120 min, achieving a maximum fluoride removal efficiency of 89.3%. The adsorption process followed the Freundlich isotherm (R^2 = 0.9976), indicating multilayer heterogeneous adsorption, while pseudo-second-order kinetics (R^2 = 0.9988, K_2 = 0.8886) confirmed chemisorption as the dominant mechanism. The Langmuir model provided a maximum adsorption capacity of 0.318 mg/g with a separation factor (RL = 0.5982), indicating a favourable adsorption process. Model validation

showed high predictive accuracy (R^2 = 99.88%, adjusted R^2 = 99.56%, test R^2 = 98.16%) with minimal deviation (S = 1.10561). Further, SGAC's reusability was tested over five regeneration cycles using 0.1 M NaOH, with desorption efficiency declining from 89.5% to 78.3%, indicating strong fluoride interactions with functional groups. Additionally, SGAC-treated water met BIS drinking water standards, with fluoride removal ensuring a final pH of 7.4, making it safe for consumption. Overall, SGAC proves to be a highly efficient, stable, and reusable adsorbent for fluoride removal, with its cost-effectiveness and reusability enhancing its potential for sustainable groundwater treatment applications. To optimize the practical implementation of SGAC, upcoming studies should prioritize scaling production, enhancing desorption techniques, and integrating SGAC within hybrid treatment frameworks. Advanced spectroscopic analysis can provide deeper insights into fluoride binding mechanisms, while pilot-scale trials in diverse water matrices will validate its field applicability. This study is distinguished by its pioneering use of SGAC for fluoride removal, extensive material characterization, exceptional removal efficiency, and the confirmation of a solid adsorption model. With its cost-effectiveness, stability, and sustainability, SGAC presents a promising solution for large-scale groundwater treatment, addressing global concerns over fluoride contamination. Future studies should focus on scaling up SGAC production, enhancing cost-effectiveness, and ensuring suitability for large-scale groundwater treatment. By refining desorption techniques, the reusability of SGAC can be enhanced, contributing to sustainable long-term usage. Future studies should investigate the integration of SGAC within hybrid treatment systems, pairing it with alternative adsorbents or filtration approaches to elevate fluoride removal efficiency across different water types. Surface characterization techniques, such as XPS or NMR, should assist in understanding fluoride binding mechanisms and optimizing surface properties for improved adsorption.

AUTHOR CONTRIBUTIONS

D. Sivakumar conceptualized the study, supervised the study, guided the research process, and contributed to data interpretation, analysis, and report preparation. M. Perarul Selvan conducted the experiments, collected and analyzed the data, and contributed to writing and editing the report. J. Nouri contributed to the study's conceptual framework and provided critical insights for research development. M. Juhi Jabin assisted in experimental setup, data validation, and manuscript formatting. S. Priyanka assisted in statistical analysis, literature review, and final proofreading of the manuscript. G. Madhubala contributed to sample preparation, chemical analysis, and graphical data representation. All authors contributed equally to the completion of the study and approved the final manuscript.

ACKNOWLEDGEMENT

The authors express their sincere gratitude to the Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu, India, for providing the necessary facilities and support to conduct this research. Special thanks to the Tehran University of Medical Sciences, Tehran, Iran, for their valuable collaboration and guidance. This project did not receive any financial support from external funding agencies.

CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims with regard to published maps and institutional affiliations.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
µm	Micrometers
3D	Three dimension
Å	Angstrom
Al	Aluminum
APHA	American Public Health Association
AWWA	American Water Works Association
BET	Brunauer-Emmett-Teller
BIS	Bureau of Indian Standards
Ca	Calcium
Cl	Chlorine
Cl_2	Chloride
cm	Centimeters
cm^3/g	Cetimeter cubes per gram
Cu	Copper
Cu 2 Theta	Coupled two theta
EDX	Energy dispersive x-ray spectroscopy
F	Fluoride
Fe	Iron
FTIR	Fourier transform infrared spectroscopy
g	Gram
g/kg	Grams per kilogram
h	Hour
IQ	Intelligence quotient
K	Potassium
KARE	Kalasalingam Academy of Research and Education
KBr	Potassium bromide
Kα	K-alpha
L/g	Liters per gram
L/mg	Liters per milligram
m^2/g	Square meters per gram
Mg	Magnesium
mg/g	Milligrams per gram
mg/L	Milligrams per liter
min.	Minute
mL	Milliliters
mm	Millimeter
mol	Mole
Na	Sodium
NaOH	Sodium hydroxide
nm	Nanometer
NO_3	Nitrate
P	Phosphorus
PAC	*Populusalba* activated carbon
pH	Potential of hydrogen
R^2	Coefficient of determination
rpm	Revolutions per minute
RSM	Response Surface Methodology
S	Sulphur
SD	Standard Deviation
SE	Standard Error
SEM	Scanning electron microscopy
SGAC	*Sesbania grandiflora* activated carbon
SO_4	Sulphate
TDS	Total Dissolved Solids

TH	Total Hardness
V	Volt
WEF	Water Environment Federation
WHO	World Health Organization
WL	Wavelength
XRD	X-ray diffraction
λ	Lambda

REFERENCES

Adam, M.R.; Othman, M.H.D.; Kurniawan, T.A.; Puteh, M.H.; Ismail, A.F.; Khongnakorn, W.; Rahman, M.A.; Jaafar, J., (2022). Advances in adsorptive membrane technology for water treatment and resource recovery applications: A critical review. J. Environ. Chem. Eng., 10(3): 107633 **(19 pages).**

Addar, F.Z.; Mohamed, I.; Kitanou, S.; Tahaikt, M.; Elmidaoui, A.; Taky, M., (2024). Performance of three anion-exchange membranes in fluoride ions removal by electrodialysis. Water Sci. Technol., 89(1): 132-145 **(14 pages).**

Al-Musawi, T.J.; McKay, G.; Kadhim, A.; Joybari, M.M.; Balarak, D., (2024). Activated carbon prepared from hazelnut shell waste and magnetized by Fe_3O_4 nanoparticles for highly efficient adsorption of fluoride. Biomass Convers. Biorefin., 14(4): 4687-4702 **(16 pages).**

Amaibi, P.M.; Egong, J.F.; Iwe, C.R.; Obunwo, C.C., (2024). Adsorption and kinetic studies for removal of fluoride in aqueous system by activated carbon produced from lemon peels. J. Appl. Sci. Environ. Manage., 28(5): 1413-1419 **(7 pages).**

APHA, (2017). Standard methods for the examination of water and wastewater, 23rd edition. AWWA; WEF, Am. Public Health Assoc., Washington D.C.

Bakhta, S.; Sadaoui, Z.; Bouazizi, N.; Samir, B.; Allalou, O.; Devouge-Boyer, C.; Mignot, M.; Vieillard, J., (2022). Functional activated carbon: from synthesis to groundwater fluoride removal. RSC Adv., 12(4): 2332-2348 **(17 pages).**

Bhaumik, R.; Mondal, N.K., (2016). Optimizing adsorption of fluoride from water by modified banana peel dust using response surface modelling approach. Appl. Water Sci., 6: 115-135 **(21 pages).**

Bonyadi, Z.; Kumar, P.S.; Foroutan, R.; Kafaei, R.; Arfaeinia, H.; Farjadfard, S.; Ramavandi, B., (2019). Ultrasonic-assisted synthesis of populus alba activated carbon for water defluorination: application for real wastewater. Korean J. Chem. Eng., 36: 1595-1603 **(9 pages).**

Chandrakera, N.; Thakura, R.S.; Chaudharib, P.K., (2021). Removal of fluoride using bagasse activated carbon. Desalin. Water Treat., 241: 112-123 **(12 pages).**

Chukka, N.D.K.R.; Gomathi Nagajothi, P.; Natrayan, L.; Reddy, Y.B.S.; Veeman, D.; Patil, P.P.; Thanappan, S., (2022). Investigation on efficient removal of fluoride from ground water using activated carbon adsorbents. Adsorpt. Sci. Technol., 2022: 7948069 **(9 pages).**

de Carvalho Costa, L.R.; Jurado-Davila, I.V.; Oliveira, J.T.D.; Nunes, K.G.P.; Estumano, D.C.; de Oliveira, R.A.; Carissimi, E.; Féris, L.A., (2024). Exploring key parameters in adsorption for effective fluoride removal: a comprehensive review and engineering implications. Appl. Sci., 14(5): 2161 **(22 pages).**

Divyadeepika.; Yadav, K.; Joshi, J., (2024). Fluoride pollution control techniques and principles. In Adv. Treat. Technol. Fluoride Removal Water: Water Purif., 43-69 **(29 pages).**

Durairaj, S., (2024). Sorption capacity of *Eichhornia crassipes* (Mart.) Solms for zinc removal from electroplating industry wastewater. Environ. Sci. Pollut. Res., 31(21): 30849-30866 **(18 pages).**

Fito, J.; Said, H.; Feleke, S.; Worku, A., (2019). Fluoride removal from aqueous solution onto activated carbon of catha edulis through the adsorption treatment technology. Environ. Syst. Res., 8(1): 1-10 **(10 pages).**

Fuentes-Gandara, F.; Piñeres-Ariza, I.; Zambrano-Arevalo, A.; Castellar-Ortega, G.; Herrera-Herrera, C., Castro-Muñoz, S.; Peluffo Foliaco, G.; Pinedo-Hernández, J., (2024). Removal of direct navy blue dye from aqueous solutions using banana peels. Global J. Environ. Sci. Manage., 10(3): 1067-1084 **(18 pages).**

George, A.M.; Tembhurkar, A.R., (2018). Biosorptive removal of fluoride from aqueous solution onto newly developed biosorbent from ficus benghalensis leaf: Evaluation of equilibrium, kinetics, and thermodynamics. Sustainable Chem. Pharm., 10: 125-133 **(9 pages).**

Ghomashi, P.; Charkhi, A.; Kazemeini, M.; Yousefi, T., (2020). Removal of fluoride from wastewater by natural and modified nano clinoptilolite zeolite. J. Water Environ. Nanotechnol., 5(3): 270-282 **(13 pages).**

Gousalya, V.; Prabu, D.; Mohan, M.R.; Dhamodhar, D.; Bharathwaj, V.V.; Sindhu, R.; Sathiyapriya, S., (2023). Effect of fluoride on oral health status among general population residing in high-and low-level fluoride blocks in Erode district, Tamil Nadu, India: A cross-sectional study. J. Pharm. Bioallied Sci., 15(Suppl 1): S752-S755 **(4 pages).**

Hu, H.; Yang, L.; Lin, Z.; Xiang, X.; Jiang, X.; Hou, L., (2018). Preparation and characterization of novel magnetic Fe_3O_4/chitosan/$Al(OH)_3$ beads and its adsorption for fluoride. Int. J. Biol. Macromol., 114: 256-262 **(7 pages).**

Huyen, D.T.; Tien, D.X.; Thoai, D.Q., (2023). Bone-char from various food-waste: Synthesis, characterization, and removal of fluoride in groundwater. Environ. Technol. Innovation., 32: 103342 **(12 pages).**

Imai, Y.; Yanagawa, S.; Konishi, M.; Kawakami, T., (2017). Removing fluoride from a hot spring using an electrolysis system. Geomate J., 12(32): 101-106 **(6 pages).**

Iwar, R.T.; Iorhemen, O.T.; Katibi, K.K., (2021). Novel aluminium (hydr) oxide-functionalized activated carbon derived from raffia palm (Raphiahookeri) shells: Augmentation of its adsorptive properties for efficient fluoride uptake in aqueous

media. Environ. Chem. Ecotoxicol., 3: 142-154 **(13 pages).**

Iwar, R.T.; Ugwudike, B.O., (2022). Groundwater fluoride removal by novel activated carbon/aluminium oxide composite derived from raffia palm shells: optimization of batch operations and field-scale point of use system evaluation. Results Eng., 14: 100407 **(12 pages).**

Jayashree, D.E.; Pooja, G.; Kumar, P.S.; Prasannamedha, G., (2020). A review on fluoride: Treatment strategies and scope for further research. Desalin. Water Treat., 200: 167-186 **(20 pages).**

Kavisri, M.; Moovendhan, M., (2024). Assessment of groundwater quality and fluoride contamination in Dharmapuri and Krishnagiri districts, Tamil Nadu, India. Environ. Q. Manage., 34(2): e70002 **(12 pages).**

Kennedy, A.M.; Arias-Paic, M., (2020). Fixed-bed adsorption comparisons of bone char and activated alumina for the removal of fluoride from drinking water. J. Environ. Eng., 146(1): 04019099 **(11 pages).**

Kumar, P.S., (2021). Groundwater fluoride contamination in Coimbatore district: A geochemical characterization, multivariate analysis, and human health risk perspective. Environ. Earth Sci., 80(6): 232 **(10 pages).**

Kumari, S.; Dhankhar, H.; Abrol, V.; Yadav, A.K., (2024). Bioaccumulation of fluoride toxicity in plants and its effects on plants and techniques for its removal. advanced treatment technologies for fluoride removal in water: Water Purification, 271-290 **(20 pages).**

Kumari, U.; Behera, S.K.; Meikap, B.C., (2019). A novel acid modified alumina adsorbent with enhanced defluoridation property: Kinetics, isotherm study and applicability on industrial wastewater. J. Hazard. Mater., 365: 868-882 **(15 pages).**

Mallishery, S.; Sawant, K.; Jain, M., (2020). Fluoride toxicity: a review on dental fluorosis and its prevalence in India. J. Dent. Med. Sci., 19: 48-53 **(6 pages).**

Nandiyanto, A.B.D.; Oktiani, R.; Ragadhita, R., (2019). How to read and interpret FTIR spectroscope of organic material. Indones. J. Sci. Technol., 4(1): 97-118 **(22 pages).**

Niyitegeka, H.; Kassahun, S.K.; Nyangi, M.J., (2023). Removal of fluoride from water using aluminum-modified activated carbon prepared from khat (Catha edulis) stems. Rem. J., 33(2): 119-133 **(15 pages).**

Onipe, T.; Edokpayi, J.N.; Odiyo, J.O., (2020). A review on the potential sources and health implications of fluoride in groundwater of Sub-Saharan Africa. J. Environ. Sci. Health. Part A., 55(9): 1078-1093 **(16 pages).**

Ousman, W.Z.; Alemayehu, E.; Luis, P., (2023). Fluoride removal and recovery from water using reverse osmosis and osmotic membrane crystallization. Clean Technol., 5(3): 973-996 **(24 pages).**

Palodkar, A.V.; Anupam, K.; Banerjee, S.; Halder, G., (2017). Insight into preparation of activated carbon towards defluoridation of waste water: optimization, kinetics, equilibrium, and cost estimation. Environ. Prog. Sustainable Energy., 36(6): 1597-1611 **(15 pages).**

Ratnani, R.D.; Purbacaraka, F.H.; Hartati, I.; Syafaat, I., (2019). Actived carbon from teak wood, jackfruit wood, and mango wood pyrolysis process. J. Phys. Conference Series., 1217(1): 012055 **(9 pages).**

Samimi, M., (2024). Efficient biosorption of cadmium by *Eucalyptus globulus* fruit biomass using process parameters optimization. Glob. J. Environ. Sci. Manag., 10(1): 27-38 **(12 pages).**

Senewirathna, D.S.G.D.; Thuraisingam, S.; Prabagar, S.; Prabagar, J., (2022). Fluoride removal in drinking water using activated carbon prepared from palmyrah (Borassus flabellifer) nut shells. Curr. Res. Green Sustainable Chem., 5: 100304 **(8 pages).**

Singh, A.; Singh, J., (2021). Effects on human health due to fluoride. Green technol. defluoridation Water. 1-16 **(16 pages).**

Solanki, Y.S.; Agarwal, M.; Maheshwari, K.; Gupta, S.; Shukla, P.; Gupta, A.B., (2021). Removal of fluoride from water by using a coagulant (inorganic polymeric coagulant). Environ. Sci. Pollut. Res., 28: 3897-3905 **(9 pages).**

Talat, M.; Mohan, S.; Dixit, V.; Singh, D.K.; Hasan, S.H.; Srivastava, O.N., (2018). Effective removal of fluoride from water by coconut husk activated carbon in fixed bed column: Experimental and breakthrough curves analysis. Groundwater Sustainable Dev., 7: 48-55 **(37 pages).**

Tan, T.L.; Nakajima, H.; Rashid, S.A., (2020). Adsorptive, kinetics and regeneration studies of fluoride removal from water using zirconium-based metal organic frameworks. RSC Adv., 10(32): 18740-18752 **(13 pages).**

Tefera, N.; Mulualem, Y.; Fito, J., (2020). Adsorption of fluoride from aqueous solution and groundwater onto activated carbon of avocado seeds. Water Conserv. Sci. Eng., 5: 187-197 **(11 pages).**

Thivya, C.; Chidambaram, S.; Rao, M.S.; Thilagavathi, R.; Prasanna, M.V.; Manikandan, S.J.A.W.S., (2017). Assessment of fluoride contaminations in groundwater of hard rock aquifers in Madurai district, Tamil Nadu (India). Appl. Water Sci., 7: 1011-1023 **(13 pages).**

Vardhan, C.V.; Srimurali, M., (2016). Removal of fluoride from water using a novel sorbent lanthanum-impregnated bauxite. Springer Plus., 5(1): 1426 **(18 pages).**

Varol, E.A.; Mutlu, Ü., (2023). TGA-FTIR analysis of biomass samples based on the thermal decomposition behavior of hemicellulose, cellulose, and lignin. Energies., 16(9): 3674 **(19 pages).**

Wang, B.; Lan, J.; Bo, C.; Gong, B.; Ou, J., (2023). Adsorption of heavy metal onto biomass-derived activated carbon. RSC adv., 13(7): 4275-4302 **(28 pages).**

Yang, F.; Jin, C.; Wang, S.; Wang, Y.; Wei, L.; Zheng, L.; Gu, H.; Lam, S.S.; Naushad, M.; Li, C.; Sonne, C., (2023). Bamboo-based magnetic activated carbon for efficient removal of sulfadiazine: Application and adsorption mechanism. Chemosphere, 323: 138-145 **(11 pages).**

Zhang, J.; Kong, Y.; Yang, Y.; Chen, N.; Feng, C.; Huang, X., (2019). Fast capture of fluoride by anion-exchange zirconium–graphene hybrid adsorbent, Langmuir, 35(21): 6861-6869 **(9 pages).**

AUTHOR (S) BIOSKETCHES

Sivakumar, D., Ph.D., Professor, Department of Agricultural Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu, India.
- Email: *d.sivakumar@klu.ac.in*
- ORCID: 0000-0001-5228-0145
- Web of Science ResearcherID: Y-6145-2019
- Scopus Author ID: 55611586900
- Homepage: http://13.235.237.27/school/school-of-bio-and-chemical-engineering-sbce/

Perarul Selvan, M., Ph.D. Candidate, Department of Agricultural Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu, India.
- Email: *m.perarulselvan@klu.ac.in*
- ORCID: 0009-0008-6628-9237
- Web of Science ResearcherID: KII-1925-2024
- Scopus Author ID: 59141413600
- Homepage: http://13.235.237.27/school/school-of-bio-and-chemical-engineering-sbce/

Nouri, J., Ph.D., Professor, [1]Department of Environmental Health Engineering, Tehran University of Medical Sciences, Tehran, Iran. [2]1137 Spectrum, Irvine, Orange County 92618 USA.
- Email: *nourijafar@gmail.com*
- ORCID: 0000-0002-9982-3546
- Web of Science ResearcherID: B-2614-2008
- Scopus Author ID: 22951700700
- Homepage: http://old.tums.ac.ir/faculties/jnouri

Juhi Jabin, M., Graduate Student, Department of Agricultural Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu, India.
- Email: *juhijabin@gmail.com*
- ORCID: 0009-0009-0295-7192
- Web of Science ResearcherID: MIN-7126-2025
- Scopus Author ID: NA
- Homepage: http://13.235.237.27/school/school-of-bio-and-chemical-engineering-sbce/

Priyanka, S., Graduate Student, Department of Agricultural Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu, India.
- Email: *priyankasaravanan0912@gmail.com*
- ORCID: 0009-0000-6641-9160
- Web of Science ResearcherID: MIN-6250-2025
- Scopus Author ID: NA
- Homepage: http://13.235.237.27/school/school-of-bio-and-chemical-engineering-sbce/

Madhubala, G., Graduate Student, Department of Agricultural Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu, India.
- Email: *madhubala852587@gmail.com*
- ORCID: 0009-0009-6118-0985
- Web of Science ResearcherID: MIN-7937-2025
- Scopus Author ID: NA
- Homepage: http://13.235.237.27/school/school-of-bio-and-chemical-engineering-sbce/

HOW TO CITE THIS ARTICLE

Sivakumar, D.; Perarul Selvan, M.; Nouri, J.; Juhi Jabin, M.; Priyanka, S.; Madhubala, G., (2025). Sesbania grandiflora activated carbon as a high-efficiency stable and reusable adsorbent for sustainable fluoride removal. Global J. Environ. Sci. Manage., 11(2): 653-676.

DOI: 10.22034/gjesm.2025.02.16

URL: https://www.gjesm.net/article_722033.html

Global J. Environ. Sci. Manage. 11(2): 677-694, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

A model designed for estimating biomass and carbon pool stock in over-mature plantations of teak; Tectona grandis

C.A. Siregar, B.H. Narendra*, I.K. Abywijaya, Pratiwi, L. Alhamd, I.W.S. Dharmawan, E.E.W. Hadi, H. Kurniawan

Research Center for Ecology and Ethnobiology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor, Jawa Barat, Indonesia

ARTICLE INFO

Article History:
Received 21 October 2024
Revised 26 January 2025
Accepted 29 February 2025

Keywords:
Allometric
Biomass
Carbon stock
Over-mature teak

DOI: 10.22034/gjesm.2025.02.17

ABSTRACT

BACKGROUND AND OBJECTIVES: Teak (Tectona grandis L.f.) plantations are essential for wood production and reducing atmospheric carbon dioxide levels by storing carbon. Allometric equations, which establish a correlation between quantifiable characteristics of trees (such as diameter, height, or volume) and their biomass and carbon content, are essential for measuring the amount of carbon stored in forests. This study seeks to fill the substantial knowledge void by formulating and confirming allometric equations that are applicable for estimating biomass and carbon stock in mature teak plantations. This study plays a significant role in informing sustainable forest management practices and refining the precision of carbon offset assessments. The primary aim of the study was to bridge the significant knowledge gap by formulating and validating allometric equations that estimate biomass and carbon stocks in over-mature teak plantations.
METHODS: The study was carried out in the Cemoro Modang teak plantation region, located in the lowland forest zone, utilizing a method of sampling known as destructive sampling. A total of ninety-five trees were analyzed, and five of these were specifically chosen for the evaluation of root biomass. The term biomass describes the aggregate mass of various tree components, which consist of roots, stems, branches, and leaves. The overall quantity of carbon present in teak trees is also assessed. The biomass of each item may be determined using the allometric relationships between the diameter at breast height and the total dry weight. In addition, the biomass of necromass, litter, and understorey were quantified to determine the amount of carbon content and carbon potential across all variables.
FINDINGS: The allometric equations derived from this work may be utilized to estimate the biomass of mature teak trees, including above-ground, below-ground, and total biomass. The estimation process involves measuring the diameter of the tree trunk at breast height. These equations demonstrate statistical reliability and can effectively estimate tree biomass across various locations, provided the climatic zones are comparable. In addition, litter, and understorey ranges from 0.78 to 18.62 tons per hectare. Biomass generation was maximized at a diameter of 99 centimeters for the teak trees. The carbon content per hectare of 199.88 tons is comparable to a potential carbon dioxide emission of 439.49 tons.
CONCLUSION: This study produces three allometric equations as: Y=0.5849 x1.9999 (adjusted coefficient of determination 0.8765, coefficient of determination 0.8778) for the above-ground biomass, Y=0.0061 x2.8128 (adjusted coefficient of determination 0.8691, coefficient of determination 0.8705) for the below-ground biomass, and Y=0.4023 x2.1539 (adjusted coefficient of determination 0.8763, coefficient of determination 0.8776) for the total biomass. This equation has proven more accurate in estimating biomass in over-mature teak trees than using equations made from samples of younger teak trees. The average estimated biomass at the plantation level was found to be 145.2 tons per hectare, accompanied by a carbon stock of 93.3 tons per hectare, which corresponds to an absorption capacity of 342.0 tons per hectare carbon dioxide equivalent.

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
82	3	5

*Corresponding Author:
Email: *budi065@brin.go.id*
Phone: +6281 2420 3265
ORCID: 0000-0001-8856-5687

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Forests hold substantial importance, delivering critical advantages for people and the natural world alike (Pandey *et al.,* 2019). Forests serve as carbon (C) absorbers from the atmosphere and store it in biomass, regulate the global climate, conserve biodiversity, protect habitats, act as water sources, and provide other environmental services. This type of vegetation contributes significantly to various environmental functions that are essential for life on Earth. It aids in soil stabilization, reduces erosion, and ensures the preservation of clean water supplies. Furthermore, forests contribute to reducing greenhouse gases (GHG) through their photosynthesis processes by absorbing carbon dioxide (CO_2) gases from the atmosphere, supporting plant growth development, and producing C biomass in forest vegetation (Agus *et al.,* 2019; Santosa *et al.,* 2020). Over the last thirty years, the escalating concentration of greenhouse gases in the atmosphere has had detrimental effects on the environment, becoming a pressing issue on both national and global scales (Raihan *et al.,* 2019; Singh *et al.,* 2020). The conversion of forests into agricultural land, pasture, or other functions by cutting down trees will result in emissions because the C stored in the trees will be released. Approximately 25 percent of global greenhouse gas emissions are attributed to changes in land use. Three regions with the highest emissions (Latin America, Southeast Asia, and sub-Saharan Africa) have dominated the global emission growth from 1961 to 2017, driven by rapid agricultural production growth and land use changes (Hong *et al.,* 2021). Increased greenhouse gas emissions, along with global warming and climate change, have substantial and varied effects on forest ecosystems. Some of the effects include: transformed ecosystems, heightened occurrence and severity of wildfires, surges in pest and disease incidents, diminished C storage, fluctuations in water supply, alterations in species distribution, and a reduction in ecosystem services. Overall, increased greenhouse gas emissions and climate change pose significant challenges to the health and resilience of forest ecosystems worldwide. With rising apprehensions regarding global climate change, the importance of natural forests in capturing C has become a central theme in research and policy discussions (Chen *et al.,* 2021). Forests, particularly those dominated by valuable timber species such as teak (*Tectona grandis* L.f.) plantation, play a crucial role in timber production and mitigating atmospheric CO_2 levels through C sequestration. Teak, popular for its slow growth rates and long rotation (Ginting and Prayogo, 2018), presents an interesting case for understanding various C dynamics in forest ecosystems. Consequently, determining the amount of C captured in living biomass is a crucial domain of study. Allometric equations that relate trees' measurable attributes (such as diameter, height, or volume) to their biomass and C content are indispensable tools for estimating forest C stocks (Kenzo *et al.,* 2020; Yang *et al.,* 2023). While various equations have been created for multiple tree species, there is a considerable deficiency in the understanding of over-mature teak plantations, especially those that have reached approximately 80 years of age and are in their later growth phases. As is known, stems with large diameters store more biomass and C than trees with smaller diameters (Mildrexler *et al.,* 2020; Lutz *et al.,* 2018; Kohl *et al.,* 2017). Mature teak plantations represent unique C reservoirs due to their substantial biomass accumulation over time, making them valuable assets in climate change mitigation efforts (Pandey *et al.,* 2019). Moreover, the C content observed during each growth phase of trees in both natural forests and plantations demonstrated that variations in annual ring widths did not affect the C content within the wood (Khantawan *et al.,* 2019). To accurately quantify the C sequestered by over-mature teak plantations, it is essential to establish robust allometric equations tailored to this species and age class. These equations will enable accurate assessment of C stocks both above and below ground through destructive measurements, providing valuable guidance for forest management and climate policy. It was hypothesized that the biomass patterns of mature teak stands differ from those of younger or smaller tree stands. This study builds upon existing efforts in forest C accounting and contributes new insights into the C dynamics of managed teak forests. By highlighting the C sequestration capabilities of over-mature teak plantations, this study intends to guide sustainable forest management practices and refine the accuracy of C offset assessments as part of climate change mitigation strategies. The development of an allometric equation on over-mature is almost none, hence this observation was specially designed to provide the gap, which is very

critical in the estimation of biomass of teak plantation. The findings of this study can be a reference for those who propose carbon trading activities or reducing emissions from deforestation and forest degradation (REDD+) initiatives in calculating the C stocks of teak plantation forests using the Tier 3 approach or using specific local allometric equations. Employing localized allometric equations can enhance the precision and diminish the uncertainty surrounding C stock estimates, which in turn affects the smaller uncertainty buffer associated with the valuation of carbon credits aimed at emission reductions (Mulatu *et al*., 2024; Adediran *et al*., 2023). This study aims to address the critical knowledge gap by developing and validating allometric equations for estimating biomass and C stocks in over-mature teak plantations. The current study has been carried out in the teak plantation area of Perhutani in Blora Regency, Central Java Province, Indonesia, performed in 2021.

MATERIALS AND METHODS

Description of the study area

The study was conducted in the teak plantation area of Perhutani. This state-owned company is also part of the Cemoro Modang research forest, geographically located at 111°32' - 111°33' East Longitude and 7°03' - 7°05' South Latitude, and administratively located in Blora Regency, Central Java Province (Fig. 1). This location has a type D (moderate) climate based on Schmidt and Ferguson climate classification, with mean annual precipitation 1710 millimeters (mm). The average air temperature is 25.0 degrees Celsius



Fig. 1: Geographic location of the study area in Blora Regency, Central Java Province, in the teak plantation area of Perhutani, Indonesia

(°C) - 27.9°C, with average air humidity ranging from 61.9% - 74.5% (Nugroho and Riyanto, 2020; Prasojo *et al*., 2025).

This area exhibits a topography that transitions from flat to gently sloped, with soil classifications of Inceptisols and Entisols. Teak, the predominant species, was introduced in 1941, with a planting density of 72 trees per hectare (Nugroho and Riyanto, 2020). Unlike teak stands in general, which have a harvest age of around 40 years (Chayaporn *et al*., 2021), the teak at this location has already passed maturity (over-mature trees) and only started to be cut at more than eighty years of age.

Data collection

In this research, biomass and C content were determined at the tree level and plantation level (Chayaporn *et al*., 2021). The destructive sampling method is employed to directly measure biomass at the tree level. Destructive sampling provides high accuracy in measuring biomass and C stocks, but for large-scale applications, this method potentially disrupts ecosystems, time-consuming, and expensive. The integration of field diameter at breast height (DBH) measurements with remote sensing technologies—such as satellite images, drones, light detection and ranging (LiDAR), and terrestrial laser scanning (TLS)—will significantly improve the efficiency of assessments conducted over extensive landscapes (Larekeg *et al*., 2024; Basyuni *et al*., 2025; Singhal *et al*., 2021). Findings from the study by Singhal *et al*. (2021) indicate that the destructive method is the most reliable for estimating C stock in trees, compared to TLS techniques, global allometric equations with assigned C content and wood density values, and local allometric equations derived from field measurements of C content and wood density. The research was conducted in an area with ~939 teak trees with a range of DBH varying from 24 centimeters (cm) and 93 cm. Based on this range, five diameter classes were created and each diameter class was represented by 15 to 18 trees using stratified random sampling, so that overall there were 95 trees cut down. Each felled tree was divided into different tree sections, namely the main stem, stump, branches, twigs, and leaves, which will be used to calculate above-ground biomass (AGB) (Ngoma *et al*., 2018). To enhance the accuracy of weighing and measuring dendrometric variables, such as stem diameter and length, the main stem and branches were divided into several pieces (Aguilar *et al*., 2019). For the purpose of calculating the actual stem volume with Smallian's formula, the length and diameter of each cut segment of the main stem are measured at both ends as variable data (Basuki *et al*., 2020). Next, each tree section (branches, twigs, and leaves) is weighed to obtain fresh weight in the field. Representative material samples in each tree section were around 300 grams (g) each. For each section of the trees, samples were obtained from five felled trees, ensuring that each tree corresponded to one of the five DBH categorie (Adinugroho *et al*., 2023). Root excavation was also done on the five felled trees to obtain below-ground biomass (BGB) data. The root excavation method has results with a high level of accuracy in formulating the root-shoot ratio (RSR), but this method is known to be high cost and labor required and takes a long time because it is done manually and very carefully. This study takes into account that root excavation was performed individually, ensuring that each DBH class is properly represented (Addo-Danso *et al*., 2016). The root system obtained from each tree was cleaned of still attached soil and weighed to obtain fresh-root weight data (Kenzo *et al*., 2020). To approximate the fresh weight of the other 90 tree roots, we utilized the ratio of the fresh weight of the above-ground parts to that of the root systems from the five trees that were excavated. For laboratory analysis, a representative root sample of about 300 g was collected. At the plantation level, biomass per unit area is obtained by combining individual tree biomass data with litter and understorey biomass data (necromass is also considered but not found in this research location). The litter and understorey were obtained from 15 observation plots measuring 2 meters (m) x 2 m. In each designated plot, the litter and understorey that have been collected are weighed to ascertain their fresh weight, with representative samples of roughly 300 g being extracted for laboratory analysis (IPCC, 2006; NSAI, 2011). To determine the sample moisture content, the representative samples of tree section (main stem, branches, twigs, leaves, roots), litter, and understorey, which have been weighed in the field, were dried at 85°C to constant weight for 72 hours and weighed (Chaturvedi and Raghubanshi, 2015). Wood density is measured by weighing a small portion of each main stem and root sample in the

field, followed by calculating its volume (fresh-wood volume) through the water-displacement method (ASTM, 2022). The samples were then oven-dried and weighed to get the dry weight. Wood density expressed as grams per cubic centimeter (g/cm^3) is the division of dry weight by the volume of the wood sample Figueroa *et al.,* 2023; Joseph *et al.,* 2022). The calculation of the main stem's biomass involves multiplying its volume by the average wood density. For other parts of the tree, biomass is obtained by multiplying the fresh weight by the ratio of dry weight and fresh weight (Basuki *et al*., 2020).

Data analysis

Each tree's total biomass is the sum of AGB and BGB, where AGB is the sum of biomass of the main stem, stump, branches, twigs, and leaves, while BGB is the biomass of roots. Based on previous studies, biomass estimates for teak species were explained most accurately using power model: biomass = intercept + (DBH) power coefficient. The reliance on DBH as the only predictor variable stems largely from its practicality and robust effect size in estimating teak biomass in many tropical countries. Other important variables, including tree height, are challenging and cost-inefficient to be measured accurately for improving the performance of biomass allometric models (Kenzo *et al.,* 2020; Ngoma *et al.,* 2018; Chaturvedi and Raghubanshi, 2015). Multiple statistical models were utilized to analyze the data, specifically exponential, log-transformed, simple linear, and second-degree polynomial models, in addition to a power model consistent with earlier studies, to enable comparisons among the models. For Indonesian teak plantations, biomass allometric models have been developed in West Java (Siregar, 2012) and Yogyakarta Provinces (Aminudin, 2008), the two provinces adjacent to the province where this study site is located. Meanwhile in other countries, teak biomass allometries have also been developed in Thailand (Kenzo *et al.,* 2020) and India (Buvaneswaran *et al.,* 2006), that have been known as parts of the natural habitat of teak (Hansen *et al.,* 2017). In the model validation phase, the optimal model identified in this research, along with those from prior studies, was cross-validated by applying it to two accessible teak biomass datasets: the young to mature teak data (Kenzo *et al*., 2020) and the over-mature teak data collected in this study. The performance of each model was then evaluated and compared using several statistical measures: coefficient of determination (R^2), adjusted coefficient of determination (R^2_{adj}), root mean squared error (RMSE), mean absolute percentage error (MAPE), and Akaike Information Criteria (AIC) (Adinugroho *et al*., 2023). The value of C fractions of the main stem, branches, twigs, leaves, roots, litter, and understorey were approximated using the default value from the Intergovernmental Panel for Climate Change (IPCC) of 0.47 (IPCC, 2006). This figure was employed to evaluate the C content both above and below the surface, as well at the plantation level. At the plantation level, the average C content per tree is multiplied by the density of trees in one hectare plus the C content per hectare for litter and understorey. The estimation of CO_2 uptake in teak stands was calculated using a chemical formula as a comparison between the molecular weight of CO_2 and the mass of the C element, namely 44/12, which is used as a constant value and then multiplied by the amount of C content (Santosa *et al.,* 2020).

RESULTS AND DISCUSSION

Biomass distribution and shoot-root ratio

The insights related to the biomass of a tree species provide a compelling subject for observation and discussion. Gutiérrez *et al*. (2023) state that biomass is one of the tree growth parameters that can be used to assess several important aspects related to the sustainability of an ecosystem and environmental balance, for example, carbon, energy, and nutrient content. As indicated in Table 1, the diameter class, biomass of individual tree sections, and RSR were derived from the measurements of teak tree samples.

The analysis of the biomass content of tree sections, as in Table 1, shows that the total biomass content and each section of the tree (stem, branches, twigs, leaves, and roots) tends to increase with increasing tree diameter. As illustrated in Table 1, the upper segment comprising stems, branches, twigs, and leaves demonstrates the greatest biomass value. Sivan *et al*. (2023) explained that the main tree stem generally has more wood constituents (xylem tissue) than other tree sections (branches and twigs). The high C content in the stem is due to C being the dominant element in wood. Wood comprises cellulose, hemicellulose, lignin, and mostly extractive substances composed of C. The ratio between the

Table 1: Biomass distribution of teak according to tree sections

DBH class (cm)	N	Biomass (Kilograms per tree (kg/tree))							RSR
		Above ground					Below ground (Root)	Tree biomass	
		Stem	Branch	Twig	Leaf	AGB			
< 35	15	509.97 ± 169.2	33.78 ± 22	3.77 ± 2.2	3.21 ± 1.3	556.50 ± 182	94.45 ± 39.8	650.95 ± 221	0.16 ± 0.02
35 - 44	16	807.80 ± 222.1	56.25 ± 21.8	9.62 ± 6.8	4.58 ± 1.3	890.34 ± 234.9	189.28 ± 71.5	1079.62 ± 304.5	0.21 ± 0.03
45 - 54	18	1418.92 ± 360.2	105.13 ± 54.4	16.26 ± 10.9	6.85 ± 2.5	1566.52 ± 400.2	409.97 ± 153	1976.49 ± 551.2	0.26 ± 0.03
55 - 64	18	2008.65 ± 517.5	128.40 ± 58.9	19.16 ± 8.7	7.88 ± 2.6	2188.61 ± 543.1	660.41 ± 262.4	2849.02 ± 799	0.29 ± 0.04
> 64	16	2480.54 ± 813.1	244.04 ± 81	34.54 ± 16.9	12.33 ± 2.9	2810.63 ± 893	932.70 ± 448.9	3743.33 ± 1336.2	0.32 ± 0.05
Biomass per tree	95	1419.37 ± 845.8	110.28 ± 87.1	16.33 ± 14.1	6.85 ± 3.7	1572.63 ± 943.5	444.71 ± 379.1	2017.34 ± 1317.6	0.25 ± 0.07

Values are in the format of mean ± standard deviation (SD).

BGB (roots) and the AGB (stem, branches, twigs, and leaves) is called the root-shoot ratio (RSR). The established RSR value for a tree species is essential for estimating BGB in cases where only AGB data is available. This enables a precise and efficient assessment of BGB's role in C sequestration. This study shows that the average RSR is 0.25, as shown in Table 1. This value is similar to the average RSR teak for over five years of teak plantations in Thailand (Kenzo *et al*., 2020) and 15 years of teak plantation in Indonesia (Siregar, 2012). As noted by Patel *et al.* (2016), an increased biomass in the shoot relative to the root can enhance the shoot's ability to manage nutrient absorption. Shoots will quickly increase nutrient absorption by roots, and these nutrients are used as growth products (nucleic acids, proteins, and chlorophyll). This is suggested that the elevation in RSR results from the plants being in a state of nutrient deficiency coupled with inadequate water availability. Yan *et al*. (2020) stated that if plants lack nutrients and water, plants form more roots, which is intended to increase uptake and result in a higher RSR. In addition, temperature and precipitation are pivotal climatic factors (Gong *et al.,* 2023). Studies have shown that the interplay between temperature and moisture has a significant effect on how plants allocate their below-ground biomass (Liu *et al.,* 2021). Wang et al. (2024) revealed that climate and soil factors influence grassland biomass allocation not only directly but also indirectly by affecting soil nutrient availability. Temperature and moisture interactively influence the makeup of the soil microbial community (Zhou *et al*., 2017). Subsequently, soil microorganisms can alter their environment by modifying the surrounding soil properties or by constructing mineral structures (Philippot *et al.*, 2024).

Teak allometric equation model

Three teak allometric equation models were produced, as presented in Table 2. Using these equations, the tree's AGB, BGB, and total biomass can be estimated using DBH as a single predictor variable. These allometric equations performed considerably well (supported by the four statistical measures, i.e. R2, MAPE, RMSE, and AIC) and can be used to estimate the biomass of teak trees growing in other areas with a similar DBH ranges, age, and climatic conditions.

The application of DBH as the exclusive predictor variable for estimating tree biomass has been the most widely adopted strategy in studies aimed at developing of biomass allometric models. Estimating forest C content usually requires precise tree diameter measurements at breast height (DBH), which is critical for maintaining the health and sustainability of natural forests and measuring teak biomass in plantation forests (Wu *et al*., 2024). The allometric models examined in this study have certain limitations. The 95% confidence intervals for the intercepts (coefficient a) of the three models span zero and negative values, suggesting that biomass estimates might be zero or negative when the diameter at breast height (DBH) of the trees is very small or nearly zero. Although these estimates are certainly incorrect, careful consideration needs to be

Table 2: Allometric equation models for the teak tree at Cemoro Modang

Equations	Coefficient	Estimate	95% confidence interval	p-value	R^2	MAPE	RMSE	AIC
AGB = $a \times (DBH)^b$	*a*	0.58486509	3.2286 – -2.0589	0.0763	0.8778	0.0944	0.2218	-10.5179
	b	1.99991023	2.1516 – 1.8482	< 0.0001				
BGB = $a \times (DBH)^b$	*a*	0.00606786	3.0343 – -3.0221	< 0.0001	0.8705	0.4808	0.3225	60.5694
	b	2.81280321	3.0333 – 2.5923	< 0.0001				
Total = $a \times (DBH)^b$	*a*	0.40229097	3.1084 – -2.3038	0.0058	0.8776	0.0784	0.2391	3.7429
	b	2.1538594	2.3174 – 1.9904	< 0.0001				

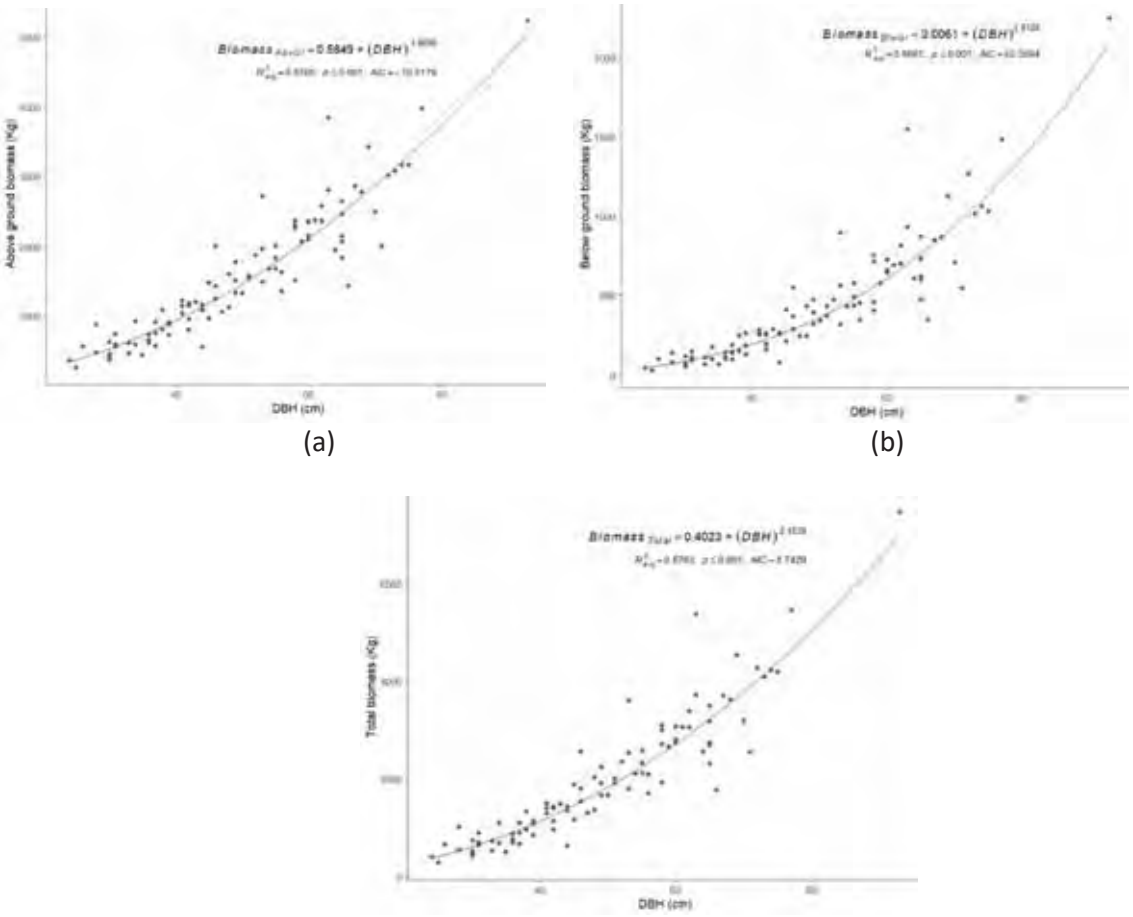


Fig. 2: Allometric equation of the relationship between DBH with (a) AGB, (b) BGB, and (c) total biomass

taken into account when using models from this study that were trained using large over-mature teak trees. Consequently, these models are intended solely for estimating the biomass of older teak trees that exhibit similar DBH ranges. The allometric relationship between DBH and AGB is depicted in Fig. 2.

The allometric equation for AGB has the highest R^2 value of 0.8778 compared to the allometric equation for BGB. It has been observed that the AGB content, which includes stems, branches, twigs, and leaves—with a notable emphasis on the stem section—is heavily influenced by the DBH variable. Consequently, this indicates that lateral growth in trees is associated with increases in other growth parameters, such as height and volume, ultimately leading to a rise in tree biomass content. Freschet *et al*. (2016) indicate that the main stem section remains a stable component of the plant, showing less biomass loss compared to

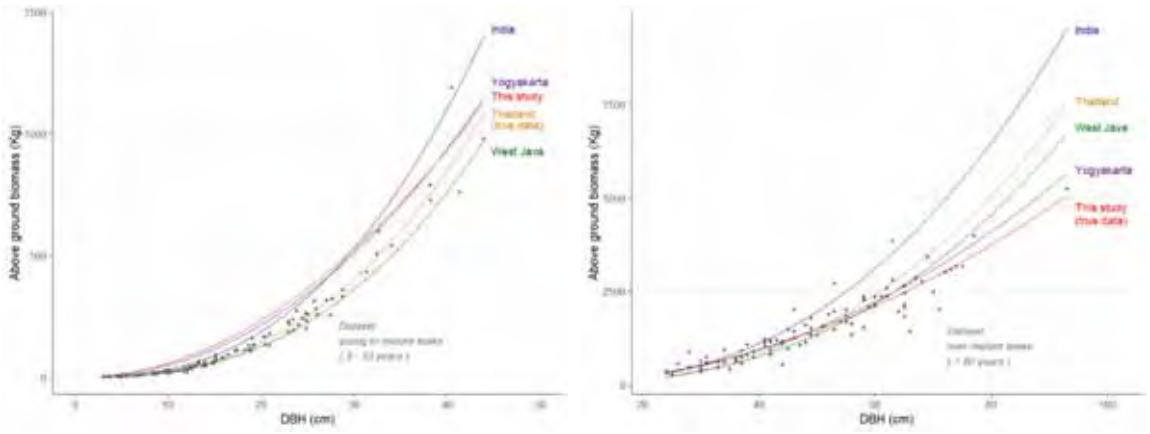
other sections like branches, twigs, and leaves. This relative stability is influenced by various external factors: a) Climatic conditions that play a crucial role in determining leaf fall during dry periods; b) Human interventions that result in the harvesting of branches and twigs for firewood; and c) Pest-related challenges, as teak leaves are vulnerable and provide nourishment for caterpillars and insects. The allometric equation for the BGB (root section) of teak trees has a lower R^2 value than the allometric equation for the ABG and total biomass. However, the R^2 is still relatively high (0.8705), which shows a high relation between DBH and root biomass, or it has a directly proportional relation. This R^2 of the allometric equation model is slightly lower than the R^2 of the allometric equation (R^2 = 0.9107) produced by Siregar (2012). Variations in root biomass in tropical forests mainly depend on climate and soil characteristics. Furthermore, another reason for the differences observed in root biomass measurements is the diverse difficulties faced when extracting roots, which can vary from site to site. Difficulties in extracting root biomass often lead to lower estimations, from 30% to 40% (Lee, 2018). Allometric equations are an effective method for accurately estimating tree biomass. The resources required to establish this equation are quite significant (Liu *et al*., 2023a). The allometric presents the relationship between the growths of different tree sections. If the correlation between diameter at DBH and total biomass is established, estimating the total biomass of a forest stand becomes a straightforward task. Only by measuring each tree's DBH can it be estimated the biomass and C stock in a forest stand (Siregar, 2012). This study focuses on the preparation of allometric equations for the over-mature teak (80 years old). Unlike previous studies, the preparation of allometric studies in this context is characterized by the age of the teak stands. Previous allometric equations focused more on the age of teak stands up to 60 years in the Asia and Latin America regions (Kenzo *et al.*, 2020). Consequently, the findings of this study can enhance existing allometric equations by providing insights related to the age classification of. This study carried out the preparation of allometric equations directly in the field using destructive sampling which has a different character from the results of other teak allometric equation studies using the satellite image NDVI value approach (Aguilar *et al*., 2019). The application of this NDVI value has proven effective in estimating C stocks in secondary forests, with results demonstrating a high level of accuracy (Frianto *et al*., 2024). Based on Fig. 2, the DBH variable is an excellent predictor parameter for estimating the total biomass content, above-ground and below-ground biomass. R^2 indicates how well the equation model can elucidate the diversity among the dependent variables. In this study, the R^2 for all equations is approaching a value of 0.88 or more, indicating that there is more diversity in the dependent variable (biomass) caused by the regression model so that the allometric model can be relied on to explain the diversity of biomass content parameters in teak trees (Kenzo *et al*., 2020). The allometric equation from this research can be used appropriately, especially for the DBH range of 35 cm to > 65 cm. It is important to note that biomass accumulation patterns in over-mature teak differ from the younger plantation (smaller diameter), and that is true because the rate growth of younger teak (1 to 25-year-old plantation) is higher than that of mature teak plantation (25 to 80-year-old plantation) (Bahtiar *et al*., 2023). The equations formulated for estimating biomass in this study demonstrated a high level of accuracy specifically for over-mature teak stands, as they take into consideration the unique biological and ecological characteristics of the teak species. However, variations in species, forest types, and ecological succession can influence the allometric of tree biomass in tropical forests (Adinugroho et al., 2023). Therefore, this equation is not suitable for use in mixed-species plantations.

Comparison with other teak allometric models

Comparison of AGB equations between values obtained in this study and existing equations from teak plantations in West Java (Siregar, 2012), Yogyakarta Provinces (Aminudin, 2008), Thailand (Kenzo *et al.*, 2020), and India (Buvaneswaran *et al.*, 2006) showed that there was a different trend among the teak plantations (Fig. 3).

These five allometric equations delineate different areas where the biomass estimates appear to be significantly inflated in comparison to the equation utilized in this study. Based on several evaluation indicators, this study's equation has better accuracy, indicated by higher R^2, RMSE, and MAPE) as stated in Table 3.

The domestic allometric models, especially from



(a) (b)

Fig. 3: Comparison of five teak biomass allometric models' trajectory estimates when cross-validated using (a) young to mature teak, and (b) over-mature teak datasets

Table 3: Comparison of thefive allometric models' performance when cross-validated using young to mature and over-mature teak datasets

Equation	Location	Teak age (years)	R^2	RMSE	MAPE
Model cross-validation using over-matured teak dataset from this study					
$AGB = 0.5849 \times (DBH)^{1.9999}$	Central Java (this study)	> 80	0.88	0.22	0.09
$AGB = 0.0562 \times (DBH)^{2.5792}$	West Java	6 – 15	0.79	434.8	20.83
$AGB = 0.3696 \times (DBH)^{2.1253}$	Yogyakarta	6 – 10	0.85	359.6	17.48
$AGB = 0.0649 \times (DBH)^{2.5702}$	Thailand	5 – 33	0.68	527.9	21.38
$AGB = 0.0904 \times (DBH)^{2.551}$	India	20 – 47	-0.17	1014.5	39.22
Model cross-validation using young to mature teak dataset from Kenzo *et al.*, 2020					
$AGB = 0.5849 \times (DBH)^{1.9999}$	Central Java (this study)	> 80	0.85	82.2	106.87
$AGB = 0.0562 \times (DBH)^{2.5792}$	West Java	6 – 15	0.94	50.2	14.49
$AGB = 0.3696 \times (DBH)^{2.1253}$	Yogyakarta	6 – 10	0.89	71.3	79.70
$AGB = 0.0649 \times (DBH)^{2.5702}$	Thailand	5 – 33	0.96	40.8	12.15
$AGB = 0.0904 \times (DBH)^{2.551}$	India	20 – 47	0.83	86.2	34.50

Yogyakarta Province, have almost resulted similar trend to this study model. From Fig. 3, it can be seen that at a small DBH class, the difference in estimated biomass produced tends to be smaller, and the difference gets bigger as the DBH increases. The first set of three equations is generated from the biomass of teak trees that grow on the same island. The differences in estimation results can be caused by teak tree samples with a DBH of 5-27 cm in the age range of 6-15 years. Likewise, the allometric model of teak plantations in other Southeast Asian countries, although the tree samples have a much older age range (Thailand 5-33 years old; India 20-47 years old) and relatively larger DBH (Thailand 3-44 cm; India 10-59 cm) compared to plant samples in West Java and Yogyakarta (Kenzo *et al.*, 2020; Buvaneswaran *et al.*, 2006). Nonetheless, the allometric data from these two countries also display more pronounced deviations, especially in the larger DBH classes. Besides the age differences among the sampled teak trees, the variations in estimation results shown in Fig. 3 could also be attributed to climatic conditions, genetic influences, or the fertility of the soil (Kenzo *et al.*, 2020; Orrego *et al.*, 2021; Waring and Powers, 2017). Several traits, including leaf size, leaf dark respiration rate, specific leaf area (SLA), leaf nitrogen and phosphorus concentrations, seed size, and wood density, exhibit large-scale correlations with climatic and soil conditions (Wright *et al.*, 2017; Atkin *et al.*, 2015; Asner *et al.*, 2016). Joswig *et al.* (2022) highlight that the combined influence of climate and soil variables consistently exceeds

the effect of each factor individually, underscoring the strong interaction between specific climatic and soil predictors. According to the findings of Chen *et al*. (2024), the chemical characteristics of soil are crucial in accounting for differences in leaf traits, suggesting that modifications in these traits do not always directly reflect climatic changes. Meanwhile, He *et al*. (2023) emphasized that plant genotype and soil physicochemical properties are the primary determinants of plant performance. Furthermore, the content of active components is influenced collectively by plant genotype, climatic conditions, and the physicochemical properties of the soil (He *et al*., 2023). The study location has a mean annual precipitation of 1710 mm, lower than locations in West Java and Yogyakarta, with mean annual precipitation of 2500 mm and 2000 mm, respectively (Siregar, 2012; Aminudin, 2008). The concentration of organic matter in the soil plays a crucial role in determining the C storage capabilities of teak wood at different age classes. The accumulation of more organic matter in the soil may boost the ability of teak trees to store C, since organic matter plays a crucial role in C sequestration processes (Ginting and Prayogo, 2018). The biogeographical zone plays a role in explaining AGB variation, although its contribution to improving AGB model accuracy is relatively minor (Manuri *et al*., 2017). Moreover, Simmavong *et al*. (2025) highlighted that forest structure plays the most significant role in positively influencing aboveground biomass. These findings emphasize the critical need to prioritize forest structure while also recognizing the scale-dependent influences of aboveground biomass drivers in efforts related to forest management and restoration. Such an approach can enhance forest C sequestration and contribute to climate change mitigation. Based on the discussion above, it can be understood that, in addition to climate and soil, the biogeographical zone and plantation management can be external factors influencing AGB.

Carbon stock of the teak tree, understorey, and litter

Carbon stock in the teak trees aligns with its biomass content, which also increases by DBH (Table 4). The increase in biomass and C levels can be attributed to the ability of plants to absorb CO_2 from the atmosphere, which they transform into organic compounds through the process of photosynthesis, facilitating both horizontal and vertical growth. The average total C stock of teak per tree is 1295.3 kg or it can be said that the potential C storage of teak trees in Cemoro Modang is 93.3 tons/ha. This C value is higher than in Wanagama, Indonesia, with 59.9 tons/ha for a 17-year-old teak plantation (Afafi *et al*., 2022). The lower C stock was also found in Thailand, reaching 60.5 tons/ha at a 35-year-old teak plantation (Chayaporn *et al*., 2021).

The results of this study with C stock of 93.3 tons/ha are smaller when compared to C storage in age class 4 (30-40 years) of 97.8 tons/ha to age class 6 (50-60 years) of 172.3 tons/ha (Al Qassam and Prayogo, 2018). In addition, the C storage results of this study are also smaller than the C storage of age class 4 (30-40 years) of 101.7 tons/ha (Chanan and Iriany, 2014), but larger when compared to teak C stocks in mixed-teak plantation (agroforestry) in Gundih, Grobogan (Santhyami and Isnaini, 2024). The observed differences in results can be attributed to variations in site index/quality of growing place, stand density, and diameter class (Santhyami and Isnaini, 2024; Chanan and Iriany, 2014), which contribute to a decrease in C absorption among older age classes. Additionally, the intensity of land management in older age classes is generally lower than that observed in younger age classes. Over-mature teak plantation begins when teak trees are ready to be cut

Table 4: Carbon stock for each DBH class

DBH class (cm)	C stock (kg/tree)		
	Above ground	Below ground	Total
< 35	369.68 ± 121	57.04 ± 24.1	426.72 ± 144.5
35 - 44	585.51 ± 153	114.31 ± 43.2	699.81 ± 195
45 - 54	1022.12 ± 256.2	247.58 ± 92.4	1269.7 ± 347.5
55 - 64	1415.93 ± 352.1	398.82 ± 158.5	1814.75 ± 506.7
> 64	1838.35 ± 587.3	563.26 ± 271.1	2401.6 ± 854.6
C per tree	1026.76 ± 613.2	268.56 ± 228.9	1295.32 ± 839.2
C per area (tons/ha)	73.93 ± 44.2	19.34 ± 16.5	93.26 ± 60.4

Values are in the format of mean ± SD.

Table 5: Average biomass and C stock in teak plantation

Source	Biomass (tons/ha)	C (tons/ha)	CO_2 equivalent (tons/ha)
Teak trees:	145.2	93.3	342.0
- AGB	113.2	73.9	271.1
- BGB	32.0	19.3	70.9
Litter	3.9	1.8	6.7
Understorey	1.5	0.7	2.6
Total	150.9	95.8	273.8

at the age of 40 years and above. Considering the age class limit of 40 years, the annual C sequestration in 80-year-old teak stands with C storage of 93.3 tons/ha in the results of this study is 0.16 tons/ha/year. When compared to other commercial trees, like the mahagony (*Swietenia macrophylla*) in Lampung province, 88 mahagony trees were able to retain 57.42 tons of C emissions annually (Nuzir, 2022). While, Latifah *et al*. (2025) found that 1,293 pine trees in the *Pinus merkusii* plantation store an estimated 467.57 tons of C and 994.82 tons of total standing biomass. This implies that teak could retain more C than other commercially valuable tree species, including pine and mahagony. The C content of teak stands demonstrates the tree's capacity to sequester CO_2 from the atmosphere. The site's prospective worth emphasizes the significant contribution of teak trees in lowering CO_2 emissions through the process of C sequestration in their biomass and soil. As the teak stand ages, the amount of C stored in the forest grows yearly, resulting in a stronger ability to remove CO_2 from the atmosphere. Table 5 informs the potential for absorption of CO_2 gas in teak stands. According to the calculation, the teak plantation located in Cemoro Modang is capable of sequestering 342.0 tons of CO_2 per hectare from the atmosphere. Furthermore, Ginting and Prayogo (2018) elucidated that the magnitude of CO_2 absorption is contingent upon the specific equations employed and the maturity of the forests. The concentration of soil organic C in teak forests varies with the age of the trees, exhibiting significant differences among various age categories (Munishamappa *et al*., 2016).

This study not only evaluated the AGB and BGB but also computed the C stock at the plantation level by aggregating C pools from the understorey and litter, as presented in Table 5. The total C stock was 95.8 tons/ha, 93.3 tons/ha, or 97.4%, was stored in the standing trees (above and below ground). At the same time, the remaining C was distributed among the litter and understorey, with values of 1.8 and 0.7 tons/ha, respectively. The biomass and C content in the understorey and litter, although much lower than the above-ground and below-ground biomass of teak vegetation, are critical for sustaining soil fertility and facilitating a sustainable C cycle (Gerke, 2023; Craig *et al*., 2022), and as a result, they may influence soil C dynamic in over-mature teak plantation thru the increase in the soil C over time through decomposition process, and thus soil conservation phenomenon. The levels of C and nitrogen found in litter have a significant effect on the processes of decomposition, directly influencing the amount of C stored within the soil (Lyu *et al*., 2023). The value diminishes in relation to the sequence of litter and understorey. This is consistent with the outcomes of prior studies Swamy *et al*. (2023) and Fang *et al*. (2021). Further, C stock and annual sequestration in different pools will generate the database for further research on climate change studies (Verma and Jain, 2017). In various locations, especially throughout many Mediterranean areas, shrub biomass can be equally significant as tree biomass in the context of C sequestration (Pasalodos-Tato *et al*., 2015). Furthermore, bushes and shrubs serve a crucial ecological function, aiding in the restoration of ecosystems while also safeguarding soil integrity (Cerda *et al*., 2021). The base-field area strongly influences the biomass of teak stands, the number of trees, and soil fertility (Lang *et al*., 2016), as well as necromass, litter, and understory, are greatly influenced by soil fertility and microclimate (Copeland and Harrison, 2016; Ma *et al*., 2023). Conversely, tissue death and defoliation rates on less fertile soils increase (Liu *et al*., 2023b). The impact of rainfall is crucial in the weathering of soil and in determining the nutrient availability for plant growth (Moreno-Jimenez *et al*., 2019; Sehler *et al*., 2019; Geneti, 2019). Teak plants are preferred in locations with

strict dry and rainy season boundaries, compared to locations with excessive or very little rainfall (Pachas *et al*., 2019). The findings of this study indicate that the biomass of litter exceeds that of the understory. This is primarily due to the prevalence of fires that take place on the forest floor in teak forests during periods of high temperatures and low humidity. This event resulted in the loss of most of the biomass and litter in the understorey. In this study, the teak forest under investigation is managed by adhering to established standard operating procedures, which include routine pruning and thinning to manage the stand's structure effectively. According to Chayaporn *et al*. (2021), sustainable teak plantation management can contribute to climate change mitigation, aligning with sustainable development goals (SDGs) 13 and 15, as well as the Paris Agreement. With effective management of teak forests around the world and support from the teak community forest, it is possible to realize emission reductions that could account for as much as 30.7% of the European Union's Emission Reduction Target by 2030. Additionally, research by Patel and Naik (2024) indicates that C sequestration is not limited to mature teak forests; even an 18-year-old teak plantation has demonstrated its potential to store C, supporting the inclusion of teak plantations in carbon offset initiatives and climate mitigation strategies. Although forest managers follow standardized management practices, including the use of the Wolf von Wulfing (WvW) normal table, the current condition of teak forests in Java has changed compared to when the table was first developed. As noted by Rahmani *et al*. (2020), the precision of estimating stand volume with the WvW table remains to be assessed. Moreover, old-age teak stands are now rarely found in Java due to illegal logging and high market demand (Sumarti *et al*., 2017). Consequently, the outcomes of this research are extremely valuable for forest managers tasked with estimating biomass in aged teak plantations. Deciding between maintaining over-mature teak plantations and early harvesting involves weighing significant economic factors. Sustaining mature plantations provides significant timber value along with opportunities for non-timber income sources such as carbon credits and tourism. However, it also presents risks, including heightened susceptibility to diseases and natural disasters, reduced growth rates, increased maintenance expenses, and missed investment prospects. Conversely, early harvesting provides a faster return on investment, reduced risks, and increased liquidity, though at the cost of lower timber prices and potential loss of premium value. To ensure informed decision-making, it is essential to establish a detailed framework that includes market analysis, plantation evaluations, financial assessments reflecting the time value of money, risk assessments, alignment with management objectives, sustainability aspects, and tax implications, all aimed at optimizing economic outcomes. Teak plantations that are around 80 years old present a significant opportunity for C sequestration, making them strong contenders for carbon credit and offset initiatives. By participating in established frameworks such as the clean development mechanism (CDM), landowners can generate and sell carbon credits, creating financial incentives for the preservation or expansion of these valuable plantations rather than converting them for other uses. By making C sequestration financially viable, this method strengthens sustainable forest management (SFM) and aids in global climate mitigation efforts. With a remarkable C storage capacity of 93.3 tons/ha and an ability to absorb 342.0 tons/ha of CO_2 equivalent, mature teak plantations stand to qualify for carbon credit programs. This type of involvement could benefit landowners by compensating them for the upkeep or growth of teak resources, and it would also furnish corporations and governments with a feasible strategy to fulfil emissions reduction commitments. Consequently, this would align with climate policies at both national and international levels, including the Paris Agreement. However, successful implementation of these initiatives requires addressing several challenges to fully harness the potential of teak plantations in the fight against climate change.

CONCLUSION

This field study, employing the destruction approach, shows that the total biomass content in each part of the teak tree (trunk, branches, twigs, leaves, and roots) significantly increases as the tree diameter increases throughout the plant growth and development period of 80-year-old teak plantations. Among the various parts, the trunk exhibits the greatest biomass content, largely attributed to its predominant carbon-rich xylem tissue. This species is recognized for its remarkable wood density traits.

In addition, the average RSR value is approximately 0.25, indicating a contribution of root biomass of one-quarter of the aboveground biomass which is considered a sizeable amount. Consequently, this ratio is important for assessing potential root biomass in situations where only aboveground biomass data is accessible. This study, moreover, produces three statistically valid allometric equations for estimating teak tree biomass based on 0.DBH. The equations include: $Y = 0.5849\ x^{1.9999}$ (R^2adj. = 0.8765; R^2 = 0.8778) for AGB, $Y = 0.0061\ x^{2.8128}$ (R^2adj. = 0.8691; R^2 = 0.8705) for BGB, and $Y = 0.4023\ x^{2.1539}$ (R^2adj. = 0.8763; R^2 = 0.8776) for total biomass, wherein Y is biomass and X is DBH. By holding the coefficient of determination as a good criterion for mathematical equations, it is clear, in all cases the three equations have R^2 values above 0.85, indicating a high level of accuracy in predicting teak tree biomass by employing merely the DBH parameter. This powerful mathematical equation offers a significant advantage in its practical application, as it requires only DBH measurements and does not necessitate the often difficult task of measuring the height of large trees. The results of this study also showed that the developed allometric equation was more accurate in estimating the biomass of over-mature teak trees compared to the equation derived from younger teak tree samples. This enhanced accuracy results from variations in the growth patterns of sigmoid nature and the biomass accumulation in older teak trees, which generally possess larger trunk diameters and biomass accumulation. At the plantation level, calculations of biomass that encompassed standing trees, litter, and understorey vegetation showed an average estimated biomass of 145.2 tons/ha with a tree density of about 72 trees/ha. Of this total biomass, the C stored was estimated to be 93.3 tons/ha. This amount is equivalent to the ability of this teak plantation to absorb atmospheric CO_2 at the rate of 342.0 tons/ha CO_2 equivalent. Carbon stored in standing trees, both above and below the soil surface, is the largest contribution, which is around 97.4% of the total C stock at the study site. The rest came from litter and understorey vegetation, amounting to 1.8 and 0.7 tons/ha, respectively. This study makes a valuable contribution to the assessment of C stocks in 80-year-old mature teak plantations. The use of proper allometric equations can be applied to estimate the magnitude of biomass and C stored in teak trees in other locations with similar climate conditions and DBH ranges. The findings of this study provide valuable information on the regulation of growth and yield, which is essential for achieving sustainable forest management goals. Additionally, it improves the accuracy of C offset calculations in the context of climate change mitigation and the C accounting systems associated with forest plantations. In addition, information on biomass distribution and root-shoot ratio provides additional insights to estimate the contribution of roots to C sequestration, which is often difficult to measure directly in the field.

AUTHOR CONTRIBUTIONS

C.A. Siregar performed the study conception, performed research methodologies, managed data collection, analyzed the data, and drafted the manuscript. B.H. Narendra performed the research conception, performed research methodologies, managed data collection, performed data processing, and drafted the manuscript. I.K. Abywijaya performed research methodologies, performed data processing validation of results, and edited the manuscript. Pratiwi performed a literature review, analyzed the data, drafted the manuscript, and edited the manuscript. L. Alhamd compiled the data, performed data processing, analyzed the data, and drafted the manuscript. I.W.S. Dharmawan performed a literature review, performed research methodologies, drafted the manuscript, and edited the manuscript. E.E.W. Hadi performed a literature review, compiled the data, drafted the manuscript, and edited the manuscript. H. Kurniawan performed a literature review, analyzed the data, validation of results, and drafted the manuscript.

ACKNOWLEDGEMENT

The Ministry of Environment and Forestry and Perum Perhutani supported and funded this study through a memorandum of understanding number [PKS.15/SET/PK/KUM.3/12/2020] on December 15th, 2020. The authors are grateful to the late Asep Sukmana, staff of Perhutani, and the Institute for Standard Implementation of Environment and Forestry Instruments of Solo, who have helped to collect the field data.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution, and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit:
http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
AGB	Above ground biomass
BGB	Below ground biomass
AIC	Akaike Information Criteria
C	Carbon
CDM	Clean development mechanism
cm	Centimeter
CO_2	Carbon dioxide
DBH	Diameter at breast height
g/cm^3	Gram per cubic centimeter
GHG	Greenhouse gases
GIS	Geographic information system
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kg/tree	Kilogram per tree
LiDAR	Light detection and ranging
m	Meter
MAPE	Mean absolute percentage error
mm	Millimeter
masl	Meter above sea level
p-value	Probability value
R^2	eCoefficient of determination
R^2_{adj}	Adjusted coefficient of determination
REDD	Reducing emissions from deforestation and forest degradation
RMSE	Root mean squared error
RSR	Root-shoot ratio
SD	Standard deviation
SE	Standard error
SFM	Sustainable forest management
SLA	Specific leaf area
TLS	Terrestrial laser scanning
tons/ha	Tons per hectare
WvW	Wolf von Wulfing

REFERENCES

Addo-Danso, S.D.; Prescott, C.E.; Smith, A.R., (2016). Methods for estimating root biomass and production in forest and woodland ecosystem carbon studies: A review. For. Ecol. Manage., 359: 332-351 (**20 pages**).

Adediran, I.A.; Swaray, R., (2023). Carbon trading amidst global uncertainty: The role of policy and geopolitical uncertainty. Econ Model., 123(106279): 1-15 (**15 pages**).

Adinugroho, W.C.; Krisnawati, H.; Imanuddin, R.; Siregar, C.A.; Weston, C.J.; Volkova, L., (2023). Developing biomass allometric equations for small trees in mixed-species forests of tropical rainforest ecozone. Trees Forests People. 13: 1-11 (**11 pages**).

Afafi, S.N.; Supartha K.I.; Fatmawati, H.; Sari, N.H.E.; Rissaldy, J.D.; Al-Husna, F.Y.; Himawan, F.D.; Aulia, M.; Ardiansyah, M.B.; Mulyana, B., (2022). Carbon Storage of Superior Clonal Teak Stand in Special Purpose Forest Area of Wanagama, Special Region of Yogyakarta. J. Galam. 2(2): 66-76 (**11 pages**).

Aguilar, F.J.; Nemmaoui, A.; Peñalver, A.; Rivas, J.R.; Aguilar, M.A., (2019). Developing allometric equations for teak plantations

located in the coastal region of Ecuador from terrestrial laser scanning data. Forests. 10: 1050 (**22 pages**).

Agus, C.; Ilfana, Z.R.; Azmi, F.F.; Rachmanadi, D.; Widiyatno; Wulandari, D.; Santosa, P.B.; Harun, M.K.; Yuwati, T.W.; Lestari, T., (2019). The effect of tropical peat land-use changes on plant diversity and soil properties. Int. J. Environ. Sci. Technol., 17(11): 1703–1712 **(10 pages**).

Al Qassam, I.; Prayogo, C., (2018). Relationship of carbon stock estimation on teak using remote sensing and field measurement. J. Tanah dan Sumberdaya Lahan, 5(1): 727-737 (**11 pages**).

Aminudin, S., (2008). Study on carbon stock potency of community forest business (Case study: Community forest of Dengok Village, Playen District, Gunungkidul Regency). Bogor: Bogor Agricultural University (**94 pages**).

Asner, G. P.; Knapp, D. E.; Anderson, C. B., Martin, R. E.; Vaughn, N., (2016). Large-scale climatic and geophysical controls on the leaf economics spectrum. Proc. Nat. Acad. Sci. USA 113: E4043–E4051 (**9 pages**).

Atkin, O. K.; Bloomfield, K.J.; Reich, P.B.; Tjoelker, M.G.; Asner, G.P.; Bonal, D.; Bonisch, G.; Bradford, M.G.; Cernusak, L.A.; Cosio, E.G.; Creek, D.; Crous, K.Y.; Domingues, T.F.; Dukes, J.S.; Egerton, J.J.G.; Evans, J.R.; Farquhar, G.D.; Fyllas, N.M.; Gauthier, P.P.G.; Gloor, E.; Gimeno, T.E.; Griffin, K.L.; Guerrieri, R.; Heskel, M.A.; Huntingford, C.; Ishida, F.Y.; Kattge, J.; Lambers, H.; Liddell, M.J.; Lloyd, J.; Lusk, C.H.; Martin, R.E.; Maksimov, A.P.; Maximov, T.C.; Malhi, Y.; Medlyn, B.E.; Meir, P.; Mercado, L.M.; Mirotchnick, N.; Ng, D.; Niinemets, Ü.; O'Sullivan, O.S.; Phillips, O.L.; Poorter, L.; Poot, P.; Prentice, I.C.; Salinas, N.; Rowland, L.M.;Ryan, M.G.; Sitch, S.; Slot, M.; Smith, N.G.; Turnbull, M.H.; Vanderwel, M.C.; Valladares, F.; Veneklaas, E.J.; Weerasinghe, L.K.; Wirth, C.; Wright, I.J.; Wythers, K.R.; Xiang, J.; Xiang, S.; Zaragoza-Castells, J., (2015). Global variability in leaf respiration in relation to climate, plant functional types and leaf traits. New Phytol., 206: 614–636 (**23 pages**).

ASTM, (2022). ASTM D2395-17 Standard Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials. ASTM International, West Conshohocken, PA. (**13 pages**).

Bahtiar, E.T.; Kim, N.H.; Iswanto, A.H., (2023). Biological rotation age of community teak (*Tectona grandis*) plantation based on the volume, biomass, and price growth curve determined through the analysis of its tree ring digitization. Forests. 14(10): 1944 (**25 pages**).

Basuki, T.M.; Pramono, I.B.; Auliyani, D., (2020). Biomass carbon stock and water yield of teak catchments. J. Degraded Min. Lands Manage., 8(1): 2481-2489 (**9 pages**).

Basyuni, M.; Amelia, R.; Aznawi, A.A.; Wirasatriya, A.; Iryanthony, S.B.; Slamet, B.; Musatniroh, S.; Rahmania,R.; Rahmila, Y.I.; Sumarga, E.; Larekeng, S.H.; Salmo III, S.; Kajita, I.; Sivaipram, I.; Ali, H.A.; Aznawi, A.A., (2025). Reduction of mangrove carbon stocks ecosystems attributed to illegal logging using combination of unmanned aerial vehicle imagery and field surveys. Global J. Environ. Sci. Manage., 11(1): 225-242 (**18 pages**).

Buvaneswaran, C.; George, M.; Perez, D.; Kanninen, M., (2006). Biomass of teak plantation in Tamil Nadu, India and Costa Rica Compared. J. Trop. For. Sci. 18(3): 195–197 (**3 pages**).

Cerda, A.; Borja, M.E.C.; Pardo, I.F.; Ubeda, X.; Novara, A.; Vicente, M.L.; Popovic, Z.; Pulido, M., (2021). The role of plant species on runoff and soil erosion in a Mediterranean shrubland. Sci. Total Environ., 799(149218):1-11 **(11 pages)**.

Chanan, M.; Iriany, A., (2014). Estimating carbon storage on teak (*Tectona grandis* Linn. F). Environ. Earth Sci., 4(3): 9-17 (**9 pages**).

Chaturvedi, R.K.; Raghubanshi, A.S., (2015). Allometric models for accurate estimation of aboveground biomass of teak in tropical dry forests of India. For. Sci. 61(5): 938–949 (**12 pages**).

Chayaporn, P.; Sasaki, N.; Venkatappa, M.; Abe, I., (2021). Assessment of the overall carbon storage in a teak plantation in Kanchanaburi province, Thailand – Implications for carbon-based incentives. Cleaner Environ. Syst., 2: 1-10 (**10 pages**).

Chen, X.; Xie, Wu, J. Q.; Zhang, H.; Li. Y., (2024). Climate and soil explain contrasting intraspecific trait variability of widespread species over a large environmental gradient. Global Ecol. Conserv., 56: e03338 (**14 pages**).

Chen, K.; Cai, Q.; Zheng, N.Y.; Li, Y.; Lin, C.; Li, Y., (2021). Forest carbon sink evaluation – An important contribution for carbon neutrality. IOP Conference Series: Earth Environ. Sci., 811(012009): 1-6 (**6 pages**).

Copeland, S.M.; Harrison, S.P., (2016). Shading and litter mediate the effects of soil fertility on the performance of an understorey herb. Ann. Bot., 118(6): 1187-1198 (**12 pages**).

Craig, M.E.; Geyer, K.M.; Beidler, K.V.; Brzostek, E.R.; Frey, S.D.; Grandy, A.S.; Liang, C.; Philips, R.P., (2022). Fast-decaying plant litter enhances soil carbon in temperate forests but not through microbial physiological traits. Nat. Commun., 13(1229): 1-10 (**10 pages**).

Fang, X.M.; Wang, G.G.; Xu, Z.J.; Zong, Y.Y.; Zhang, X.L.; Li, J.J.; Wang, H.; Chen, F.S., (2021). Litter addition and understorey removal influenced soil organic carbon quality and mineral nitrogen supply in a subtropical plantation forest. Plant Soil. 460:527-540 **(14 pages)**.

Freschet, G.T.; Kichenin, E.; Wardle, D.A., (2016). Explaining within-community variation in plant biomass allocation: a balance between organ biomass and morphology above vs below ground. J. Veg. Sci. 26(3): 431-440 (**10 pages**).

Frianto, D.; Sutrisno, E.; Wahyudi, A.; Novriyanti, E.; Adinugroho, W.C.; Yunianto, A.S.; Kurniawan, H.; Khotimah, H.; Windyoningrum, A.; Dharmawan, I.W.S.; Tata, H.L.; Suharti, S.; Rachmat, H.H.; Lim, E.M., (2024). Carbon stock dynamics of forest to oil palm plantation conversion for ecosystem rehabilitation planning. Global J. Environ. Sci. Manage., 10(4): 1593-1614 (**22 pages**)**.**

Geneti, T.Z., (2019). Review on the Effect of Moisture or Rain Fall on Crop Production. Civil Environ. Res., 11(2): 1-7 (**7 pages**).

Gerke, J., (2022). The Central Role of Soil Organic Matter in Soil Fertility and Carbon Storage. Soil Syst., 6(33): 1-14 (**14 pages**).

Ginting, T.T.; Prayogo, C., (2018). Estimation of carbon stock of teak forest (*Tectona grandis* Linn. F), using various allometric equations on various age classes of teak. J. Tanah dan Sumberdaya Lahan. 5(2): 1019-1026 (**8 pages**).

Gong, H.; Song, W.; Wang, J.; Wang, X.; Ji, Y.; Zhang, X.; Gao, J., (2023). Climate Factors Affect Forest Biomass Allocation by Altering Soil Nutrient Availability and Leaf Traits. J. Integr. Plant Biol. 65: 2292–2303 (1**2 pages**).

Gutiérrez, G.V.; Pérez, D.P.; Raczka, N.; Pereira-Arias, D.; Tijerín-Triviño, J.; Pereira-Arias, L.D.; Medvigy, D; Waring, B.G.; Morrisey, E.; Brzostek, E.; Powers, J.S., (2023). Throughfall exclusion and fertilization effects on tropical dry forest tree plantations, a large-scale experiment. Biogeoscience. 20: 2143–2160 (**18 pages**).

Hansen, O.K.; Changtragoon, S.; Ponoy, B.; Lopez, J.; Richard, J.; Kjær, E.D., (2017). Worldwide translocation of teak—origin of landraces and present genetic base. Tree Genet. Genomes. 13(87): 1-16 (**16 pages**).

He, C.; Han, T.; Liu, C.; Sun, P.; Liao, D.; Li, X., (2023) Deciphering the effects of genotype and climatic factors on the performance, active ingredients and rhizosphere soil properties of Salvia miltiorrhiza. Front. Plant Sci., 14: 1110860 (**15 pages**).

Hong, C.; Burney, J.A.; Pongratz, J.; Nabel, J.E.M.S.; Mueller, N.D.; Jackson, R.B.; and Davis SJ., (2021). Global and regional drivers of land-use emissions in 1961–2017. Nature. 589: 554-579 (**27 pages**).

IPCC, (2006). Guidelines for National Greenhouse Gas Inventories. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Intergovernmental Panel on Climate Change. The Institute for Global Environmental Strategies (IGES), Japan (**708 pages**).

Joseph, J.; James, D.; Chai, L.T.; Korom, A.; Wong, W.V.C.; Maripa, R.D.; Phua, M.H., (2022). Assessing intraspecific wood density variations of Syzgium sp. in tropical forest of Southwest Sabah. IOP Confeence Series: Earth Environ. Sci., 1053(1): 012014 (**7 pages**).

Joswig, J.S.; Wirth, C.; Schuman, M.C.; Kattge, J.; Reu, B.; Wright, I.J.; Sippel, S.D.; Rüger, N.; Richter, R.; Schaepman, M.E.; van Bodegom, P.M.; Cornelissen, J.H.C.; Díaz, S.; Hattingh, W.N.; Kramer, K.; Lens, F.; Niinemets, Ü.; Reich, P.B.; Reichstein, M.; Römermann, C.; Schrodt, F.; Anand, M.; Bahn, M.; Byun, C.; Campetella, G.; Cerabolini, B.E.L.; Craine, J.M.; Gonzalez-Melo, A.; Gutiérrez, A.G.; He, T.; Higuchi, P.; Jactel, H.; Kraft, N.J.B.; Minden, V.; Onipchenko, V.; Peñuelas, J.; Pillar, V.D.; Sosinski, Ê.; Soudzilovskaia, N.A.; Weiher, E.; Mahecha, M.D., (2022). Climatic and soil factors explain the two-dimensional spectrum of global plant trait variation. Nat. Ecol. Evol., 6(1): 36–50 (**15 pages**).

Kenzo, T.; Himmapan, W.; Yonedac, R.; Tedsorn, N.; Vacharangkura, T.; Hitsuma, G.; Nodaa, I., (2020). General estimation models for above- and belowground biomass of teak (*Tectona grandis*) plantations in Thailand. For. Ecol. Manage., 457 (117701): 1-12 (**12 pages**).

Khantawan, C.: Duangsathaporn, K.: Prasomsin, P., (2019). Relationship between carbon content and growth of teak in natural forest and plantation, Lampang Province, Thailand. Agr. Nat. Resour., 53(3): 267-273 (**7 pages**).

Kohl, M.; Neupane, P.R.; Lotfiomran, N., (2017). The impact of tree age on biomass growth and carbon accumulation capacity: A retrospective analysis using tree ring data of three tropical tree species grown in natural forests of Suriname. PLoS ONE. 12(8): 1-17 (**17 pages**).

Lang, M.; Lilleleht, A.; Neumann, M.; Bronisz, K.; Rolim, S.G.; Seedre, M.; Uri, V.; Kiviste, A., (2016). Estimation of aboveground biomass in forest stands from regression on their basal area and height. Forest. Stud., 64(1): 70–92 (**23 pages**).

Larekeng, S.H.; Nursaputra, M.; Mappiasse, M.F.; Ishak, S.; Basyuni, M.; Sumarga, E.; Arifanti, V. B.; Aznawi, A.A.; Rahmila, Y.I.; Yulianti, M.; Rahmania, R.; Mubaraq, A.; Salmo III, S. G.; Ali, H.M.; Yeni I., (2024). Estimation of mangrove carbon stocks using unmanned aerial vehicle over coastal vegetation. Global J. Environ. Sci. Manage., 10(3): 1133-1150 (**18 pages**).

Latifah, S.; Fachrudin, K.A.; Fadhilla, S.; Nurrochmat, D.R.; Simanjuntak, A., (2025). Estimation of biomass and carbon storage of *Pinus merkusii* for ecological sustainability at the Sipinsur Geosite Ecotourism. IOP Conference Series: Earth Environ. Sci. 1445 012022 (**7 pages**).

Lee, J., (2018). Relationship of root biomass and soil respiration in a stand of deciduous broadleaved trees—a case study in a maple tree. J. Ecol. Environ., 42: 19 (**8 pages**).

Liu, Y.; Cordero, I.; Bardgett, R.D., (2023a). Defoliation and fertilsiation differentially moderate root trait effect on soil abiotic and biotic properties. J. Ecol., 2023(111): 2733-2749 (**17 pages**).

Liu, B.; Bu, W.; Zang, R., (2023b). Improved allometric models to estimate the aboveground biomass of younger secondary tropical forests. Global Ecol. Conserv. 41: e02359 (**11 pages**).

Liu, R.; Yang, X.; Gao, R.; Hou, X.; Huo, L.; Huang, Z.; Cornelissen, J.H.C., (2021). Allometry Rather than Abiotic Drivers Explains Biomass Allocation among Leaves, Stems and Roots of Artemisia across a Large Environmental Gradient in China. J. Ecol. 109: 1026–1040 (**15 pages**).

Lutz, J. A.; Furniss, T. J.; Johnson, D. J.; Davies, S. J.; Allen, D.; Alonso, A.; Anderson-Teixeira, K.J.; Andrade, A.; Baltzer, J.; Becker, K.M.; *et al*., (2018). Global Importance of large-diameter trees. Glob. Ecol. Biogeogr., 27(7): 849–864 (**15 pages**).

Lyu, M.; Homyak, P.M.; Xie, J.; Peñuelas, J.; Ryan, M.G.; Xiong, X.; Sardans, J.; Lin, W.; Wang, M.; Chen, G.; Yang, Y., (2023). Litter quality controls trade off in soil carbon decomposition and replenishment in a subtropical forest. J. Ecol., 111(10): 2181-2193 (13 pages).

Ma, Q.; Su, Y.; Niu, C.; Ma, Q.; Hu, T.; Luo, X.; Tai, X.; Qiu, T.; Zhang, Y.; Bales, R.C.; Liu L.; Kelly, M.; Guo, Q., (2023). Tree mortality during long-term droughts is lower in structurally complex forest stands. Nat. Commun., 14:7467 (**11 pages**).

Munishamappa, M.; Santhoshkumar, A.; Kunhamu, T.; Sasidharan, S.; Kumar, S.; Sureshkumar, P., (2016). Organic Carbon and Total Nitrogen Status of Soils under the Teak Plantations of Various Ages in Kerala. Environ. Ecol., 34(2): 882-886 (**5 pages**).

Moreno-Jiménez, E.; Plaza, C.; Saiz, H.; Manzano, R.; Flagmeier, M.; Maestre, F.T., (2019). Aridity and reduced soil micronutrient availability in global drylands. Nat. Sustainable. 2: 371-377 (**7 pages**).

Mildrexler, D.J.; Berner, L.T.; Law, B.E.; Birdsey, R.A.; Moomaw, W.R., (2020). Large Trees Dominate Carbon Storage in Forests East of the Cascade Crest in the United States Pacific Northwest. Front. For. Global Change. 3(594274): 1-15 (**15 pages**).

Mulatu, A.; Negash, M.; Asrat, Z., (2024). Species specific allometric models for reducing uncertainty in estimating above ground biomass at Moist Evergreen Afromontane Forest of Ethiopia. Sci. Rep., 14(1147): 1-11 (**11 pages**).

NSAI, (2011). SNI 7725: 2011 Penyusunan persamaan alometrik untuk penaksiran cadangan karbon hutan berdasar pengukuran lapangan. National Standardization Agency of

Indonesia. Ground based forest carbon accounting. NSAI, Jakarta (**27 pages**).

Nugroho, W.A.; Riyanto, H.D., (2020). Study of light intensity in riparian zone of teak production forest in KHDTK Cemoro Modang. J. Waisan. 7(1): 15-24 (**10 pages**).

Ngoma, J.; Moorse, E.; Kruijtd, B.; Speerc, J.H.; Vinyaa, R.; Chidumayog, E.N.; Leemansb, R., (2018). Below and aboveground carbon distribution along a rainfall gradient. A case of the Zambezi teak forests, Zambia. Acta Oecologia. 87: 45-57 (**13 pages**).

Nuzir, F.A.; Kurniawan, A.; Chandra, S.D.; Jamaludin; Munawaroh, A.S., (2022). Study on the potential of historical mahogany trees in improving urban air quality. Int. J. Build. Urban Interior Landscape Technol., 19(1): 63-72 (**10 pages**).

Orrego, S.; Montes, C.; Restrepo, H.I.; Zapata, M. 2021. Modeling height growth for teak plantations in Colombia using the reducible stochastic differential equation approach. J For. Res., 32(3): 1035 – 1045 (**11 pages**).

Pandey, S.; Shukla, R.; Saket, R.; Verma, D., (2019). Enhancing carbon stocks accumulation through forest protection and regeneration. A review. Int. J. Environ., 8(1): 16–21 (**6 pages**).

Pachas, A.N.A.; Sakanphet, S.; Midgley, S.; Dieters, M., (2019). Teak (*Tectona grandis*) silviculture and research: applications for small holders in Lao PDR. Aust. For., 82(S1): 94–105 (**12 pages**).

Pasalodos-Tato, M.; Ruiz-Peinado, R.; del-Rio, M.; Montero, G., (2015). Shrub biomass accumulation and growth rate models to quantify carbon stocks and fluxes for the Mediterranean region. Eur. J. Forest. Res., 134: 537–553 (**17 pages**).

Patel, S.; Sawyer, J.E.; Lundvall, J.P.; Hall, J., (2016). Root and shoot biomass and nutrient composition in a winter rye cover crop. Proceeding of 45th North Central Extension-Industry Soil Fertility Conference. 31: 113-118 (**6 pages**).

Patel, S.K.; Naik, M.L., (2024). Assessment of Biomass, Carbon Stock and Sequestered CO2 in Teak (*Tectona grandis* L.f.) Plantation at Pt. Ravishankar Shukla University Campus, Raipur, Chhattisgarh, India. J. Global Ecol. Environ. 20(4): 102-114 (**13 pages**).

Philippot, L.; Chenu, C.; Kappler, A.; Rillig, M.C.; Fierer, N., (2024). The interplay between microbial communities and soil properties. Nat, Rev, Microbiol., 22(4): 226–239 (**14 pages**).

Prasojo, Y.S.; Prasetyo, B.; Suwignyo, B., (2025). Morphology characteristic and biomass production of jack bean (Canavalia ensiformis) at different growth stages in Blora, Central Java, Indonesia. Aust J Crop Sci., 19(01):84-88 **(5 pages)**.

Rahmani, T.A.; Kristiantoro, F.; Prihanto, B.; Muhdin, (2020). Accuracy testing of Wolf von Wulfing stand table in estimating teak stand volume. IOP Conference Series: Earth Environ. Sci., 528: 012065 (**8 pages**).

Raihan, A.; Begum, R.A.; Said, M.N.M.; Abdullah, S.M.S., (2019). A review of emission reduction potential and cost savings through forest carbon sequestration. Asian J. Water Environ. Pollut., 16(3): 1–7 (**7 pages**).

Santhyami; Isnaini, A.K., (2024). The composition, structure, and standing carbon stock of teak based agroforestry systems in Gundih, Grobogan Regency, Central Java. J. Ilmu Lingkungan., 22(1): 93-99 (**7 pages**).

Santosa, S.; Umar, M.R.; Priosambodo, D.; Santosa, R.A.P., (2020). Estimation of biomass, carbon stocks, and leaf litter decomposition rate in teak *Tectona grandis* Linn plantations in city forest of Hasanuddin University, Makassar. Int. J. Plant Biol., 11(8541): 32-35 (**4 pages**).

Sehler, R.; Li, J.; Reager, J.T.; Ye, H., (2019). Investigating relationship between soil moisture and precipitation globally using remote sensing observation. J. Contemp. Water Res. Educ., 168(1): 106-118 (**13 pages**).

Singh, A.K.; Sahu, C.; and Sahu, S.K., (2020). Carbon sequestration potential of a teak plantation forest in the Eastern Ghats of India. J. Environ. Biol., 41: 770-775 (**6 pages**).

Siregar, C.A., (2012). Formulasi persamaan allometrik untuk pendugaan biomasa karbon jati (*Tectona grandis* Linn.F) di Jawa Barat. J. Penelitian Sosial dan Ekonomi Kehutanan. 9(3): 160-169 (**910 pages**).

Simmavong, T., Su, Y.; Deng, Y.; Wang, B.; Yao, Z.; Wu, J.; Sha, L.; Cao, M.; Lin, L., (2025). Forest structure predicts aboveground biomass better than community-weighted means of traits, functional diversity, topography, and soil in a tropical forest across spatial scales. For. Ecol. Manage., 578, 122457 (**12 pages**).

Singhal, J.; Srivastava, G.; Reddy, C.S.; Rajashekar, G.; Jha, C.S.; Rao, P.V.N.; Reddy, G.R.; Roy, P.S., (2021). Assessment of Carbon Stock at Tree Level Using Terrestrial Laser Scanning Vs. Traditional Methods in Tropical Forest, India. IEEE J. Selected Topics Appl. Earth Observations Remote Sens., 14: 5064 – 5071 (**8 pages**).

Sivan, P.; Rao, K.S.; Rajput, K.S., (2023). Chemical composition in juvenile and mature wood of branch and main trunk of *Leucaena leucocephala* (Lam.) de Wit. Plants, 12(23): 1-14 (**14 pages**).

Swamy, S.L.; Darro, H.; Mishra, A.; Lal, R.; Kumar, A.; Thakur, T.K., (2023). Carbon stock dynamics in a disturbed tropical forest ecosystem of Central India: Strategies for achieving carbon neutrality. Ecol. Ind., 154 (110775): 1-14 (**14 pages**).

Verma, S.; Jain, A., (2017). Carbon stock in biomass and litter in different plantation of Tropical Forest Research Institute, Jabalpur. J. Tree Sci., 36(1): 29-33 (**5 pages**).

Waring, B.G.; Powers, J.S., (2017). Overlooking what is underground: Root: shoot ratios and coarse root allometric equations for tropical forests. For. Ecol. Manage. 385: 10–15 (**6 pages**).

Wu, Y.; Gan, X.; Zhou, Y.; Yuan, X., (2024). Estimation of diameter at breast height in tropical forests based on terrestrial laser scanning and shape diameter function. Sustainability. 16(6): 1-14 (**14 pages**).

Yan, J.; Bogie, N.A.; Ghezzehei, T.A., (2020). Root uptake under mismatched distributions of water and nutrients in the root zone. Biogeoscience. 17(24): 6377–6392 (**16 pages**).

Yang, M.; Zhou, X.; Peng, C.; Ling, T.; Chen, K.; Liu, Z.; Li, P.; Zhang, C.; Tang, J.; Zou, Z., (2023). Developing allometric equations to estimate forest biomass for tree species categories based on phylogenetic relationships. For. Ecosyst., 10(100130):1-10 **(10 pages)**.

AUTHOR (S) BIOSKETCHES

Siregar, C.A. Ph.D., Professor, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *chai008@brin.go.id*
- ORCID: 0000-0003-0172-7554
- Web of Science ResearcherID: NA
- Scopus Author ID: 43661890800
- Homepage: https://brin.go.id/en/page/civitas

Narendra, B.H., Ph.D., Principal Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *budi065@brin.go.id*
- ORCID: 0000-0001-8856-5687
- Web of Science ResearcherID: ABD-5972-2020
- Scopus Author ID: 55935042500
- Homepage: https://brin.go.id/en/page/civitas

Abywijaya, I.K., MSc., Junior Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *ilha006@brin.go.id*
- ORCID: 0000-0002-3587-693X
- Web of Science ResearcherID: NA
- Scopus Author ID: 57196043028
- Homepage: https://brin.go.id/en/page/civitas

Pratiwi, Ph.D., Professor, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *prat007@brin.go.id*
- ORCID: 0000-0001-6423-2351
- Web of Science ResearcherID: IQU-1436-2023
- Scopus Author ID: 5721423229
- Homepage: https://brin.go.id/en/page/civitas

Alhamd, L., Ph.D., Senior Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *laod003@brin.go.id*
- ORCID: 0000-0002-2574-5952
- Web of Science ResearcherID: JQW-2182-2023
- Scopus Author ID: 55488921400
- Homepage: https://brin.go.id/en/page/civitas

Dharmawan, I.W.S., Dr., Senior Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *iway028@brin.go.id*
- ORCID: 0000-0002-3587-693X
- Web of Science ResearcherID: NA
- Scopus Author ID: 58097512800
- Homepage: https://brin.go.id/en/page/civitas

Hadi, E.E.W., MSc., Senior Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *etik004@brin.go.id*
- ORCID: 0000-0002-0848-4121
- Web of Science ResearcherID: NA
- Scopus Author ID: 57202288322
- Homepage: https://brin.go.id/en/page/civitas

Kurniawan, H., MSc., Senior Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta-Bogor Km 46, Cibinong 16911, Indonesia.
- Email: *hery011@brin.go.id*
- ORCID: 0000-0002-7054-0921
- Web of Science ResearcherID: NA
- Scopus Author ID: 57193558098
- Homepage: https://brin.go.id/en/page/civitas

HOW TO CITE THIS ARTICLE

Siregar, C.A.; Narendra, B.H.; Abywijaya, I.K.; Pratiwi; Alhamd, L.; Dharmawan, I.W.S; Hadi, E.E.W., Kurniawan, H., (2025). A model designed for estimating biomass and carbon pool stock in over-mature plantations of teak; Tectona grandis. Global J. Environ. Sci. Manage., 11(2): 677-694.

DOI: 10.22034/gjesm.2025.02.17

URL: https://www.gjesm.net/article_721567.html

Global J. Environ. Sci. Manage. 11(2): 695-710, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Reducing hydrogen consumption in hybrid electric vehicles using Aquila optimization algorithm

A.M. Nassef[1,*], H.E. Ghadbane[2], E.T. Sayed[3], H. Rezk[1]

[1] *Department of Electrical Engineering, College of Engineering in Wadi Alddawasir, Prince Sattam bin Abdulaziz University, Wadi Alddawasir 11991, Saudi Arabia*

[2] *Département d'Electrotechnique et Automatique, Laboratoire de Génie Électrique de Guelma, Université 8 Mai 1945, Guelma 24000, Algeria*

[3] *Chemical Engineering Department, Faculty of Engineering, Minia University, Egypt*

ARTICLE INFO

Article History:
Received 18 December 2024
Revised 23 February 2025
Accepted 24 March 2025

Keywords:
Aquila optimization algorithm
Electric vehicles
Energy management strategy
Hydrogen consumption

ABSTRACT

BACKGROUND AND OBJECTIVES: Fuel cell hybrid electric vehicles have earned significant interest owing to their superior performance and ecological advantages. Crafting an energy management approach aimed at boosting the performance of fuel cell electric vehicles by effectively managing power distribution among diverse energy sources represents a vital engineering challenge. This approach considers issues such as hydrogen consumption and efficiency. The objectives of this study were: 1) Developing a state-of-the-art energy management system for fuel cell hybrid electric vehicles to maximize electrical efficiency, reduce fuel consumption, and achieve optimal power distribution. 2) Applying the aquila optimizer to the proposed system to enhance the external energy maximization strategy.
METHODS: Metaheuristic optimization algorithms play a vital role in obtaining the best set of fuel cell electric vehicles' parameters. Among the newest and most efficient algorithms, the Aquila optimization algorithm is highly regarded. It was used in the proposed energy management strategy to optimize the approach of maximizing external energy, resulting in reduced hydrogen use and improved system efficiency. To assess the effectiveness of the proposed energy management strategy, the federal test procedure was utilized to mimic city driving conditions, allowing for a comparative simulation against eight proficient algorithms.
FINDINGS: The simulation findings illustrated that the suggested energy management strategy surpasses other currently available solutions resulting from competitive optimizers by reducing the consumption of fuel, with a considerable decrease of 52.26 percent. Additionally, the recommended energy management strategy technique exhibited a 3.08 percent enhancement in system efficiency.
CONCLUSION: The proposed strategy showed outstanding results over the other methods. Moreover, advancements in the energy management strategy have the capacity to lower dependence on traditional fossil fuels and alleviate the harmful environmental consequences produced by the vehicle's emissions. Consequently, adopting a sustainable transportation framework powered by renewable hydrogen production will substantially lessen detrimental impacts and foster a cleaner and greener environment.

DOI: 10.22034/gjesm.2025.02.18

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
50

NUMBER OF FIGURES
9

NUMBER OF TABLES
2

*Corresponding Author:
Email: *a.nasef@psau.edu.sa*
Phone: +55273 4179
ORCID: 0000-0001-9604-5737

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

There is a unanimous agreement that cutting down on gas emissions is crucial for the preservation of our world. To accomplish this goal, everyone should give a hand to the development and transformation to green as well as renewable sources of energy. Examples of green energy sources include biomass, biogas, and fuel cells, whereas solar, wind, and hydro energy fall under the umbrella of renewable energy sources (Ramli *et al.,* 2022; Rashif *et al.,* 2025). The route of using alternatives to fossil fuels will lead to lowering the carbon dioxide (CO_2) emissions in order to decrease global warming by 1.5 degrees Celsius (^oC) as decided in the Conference of Parties (COP-26), which was held in Glasgow, United Kingdom (UK), in 2021 (Nassef *et al.,* 2023). In November 2024, the United Nations conducted the 29th summit of the COP-29 in Azerbaijan as a continuous effort, from its side, to tackle climate change. It is anticipated that during the upcoming COP-30, scheduled to take place in Brazil in November 2025, all prior recommendations will be translated into tangible actions. Some may argue that the emissions from one vehicle are insignificant relative to the output of an industrial factory. Nevertheless, when examining the cumulative emissions from millions of vehicles around the world, it becomes clear that the overall figure is indeed considerable. The electric vehicle is an alternating tool that uses an electric motor (electrical energy) instead of the traditional internal combustion engine (thermal energy) to obtain motion (mechanical energy). Both means give the same results (motion) however, the former is environmentally friendly and the latter is not. Within this framework, the evolution and transition to electric vehicles are progressing and have attracted considerable focus from researchers in numerous fields, particularly in engineering (Santoso *et al.*, 2024). To maximize the power delivered to the electric vehicle, an efficient energy management system (EMS) is needed to optimize the operation of the different power sources. The demand for energy has grown steadily during industrial development. Industrial progress has led to a significant increase in the need for fossil fuels (York and Bell, 2019). Hydrogen can be made as an alternative fuel by the process of either reforming carbon-based fuels or by using power from renewable sources to split water (Payakkamas *et al.*, 2023). The adoption of electric vehicles presents an encouraging approach to lowering carbon emissions in the transportation sector. For efficient reduction of CO_2 emissions, the fuel cell hybrid electric vehicle (FCEV) is an incredibly promising technology. Hydrogen fuel cells (FC) and energy storage systems (ESS) work together in FCEV technology to power the electric motor (Veziroglu and Macario, 2011). Energy savings and fuel economy are both improved by FCEV technology (Arat, 2019). FCEVs present a variety of advantages, such as not relying on fossil fuels, being compact in size, operating quietly, and delivering outstanding performance without generating any polluting emissions (Changizian *et al.*, 2020). Sivakumar (2020) conducted studies on the use of double-chambered salt bridge microbial fuel cells (MFCs) for treating dairy industry wastewater and generating bioelectricity. The optimal parameters identified were 1 molar potassium chloride (MKCl) concentration, 10 percent (%) agarose concentration, and a 0.05 meters (m) salt bridge, achieving up to 89.7% reduction in chemical oxygen demand (COD) and producing power. In a later investigation, Sivakumar (2021) reinforced these conclusions by reporting an 86.3% decrease in COD along with substantial energy output, showcasing the capability of MFCs in removing pollutants and generating power. Hidayat *et al*. (2024) focused on torrefying bamboo pellets for renewable energy in Indonesia, using a fixed counterflow multibaffle reactor. Their findings highlighted bamboo as a promising biomass source for co-firing, offering an effective solution for reducing reliance on fossil fuels and mitigating greenhouse gas emissions. As a result, electric vehicles (EVs) are expected to significantly participate in improving the future smart grids and create a sustainable transportation sector for a safe environment (Nazari-Heris *et al.*, 2022). ESS, encompassing both supercapacitors and batteries, is tasked with handling large power surges that occur during both acceleration and deceleration. On the other hand, the power system of a FCEV is completely electric (Wang *et al.*, 2023). To address the sluggish performance of fuel cells and the limited longevity of batteries, it is imperative to combine them with a high-capacity energy storage technology such as supercapacitors (SCs), which provide quick response times. Hybridization is crucial for overcoming these limitations and improving overall efficiency (Djerioui *et al.*, 2019; Sorlei *et al.*, 2021). By optimizing the operational environment of the fuel cell system,

hybridization significantly enhances its overall performance. In the electric vehicle, it is essential to devise a suitable energy management system responsible for allocating power among the hybrid power sources, taking into account certain constraints that must be satisfied to enhance performance and minimize fuel consumption. Still, the main issue at hand is the effectiveness of the chosen EMS. To attain this objective, numerous EMSs have been documented in the research literature. Generally, EMSs can be categorized into optimization and rule-based systems, as indicated in (Eddine *et al.*, 2022; Zhang *et al.*, 2020). This approach is characterized by a collection of sequential "IF-THEN" rules, which can be divided into two primary subcategories: deterministic and intelligent. The state machine control (SMC) and load following EMS are representative of the deterministic type (Ghadbane *et al.*, 2024a; Ghadbane *et al.*, 2024c). On the other hand, the intelligent strategies are represented by the fuzzy logic-based EMS (Sulaiman *et al.*, 2015). Although this system is simple to design and implement, its performance is constrained by the designer's knowledge and experience (Rahman *et al.*, 2021). Optimization-based approaches utilize tools inherent in the optimization theory to address problems, such as the one at hand. Optimization methods can be classified as either offline (global scale) or online (real-time scale). Offline optimization EMS involves identifying an optimal control solution for a predetermined situation, such as a speed profile. A range of methodologies is present, with disciplined optimum control being one that focuses on direct approaches. However, indirect techniques such as Pontryagin's maximal principle (PMP) (Bauer *et al.*, 2014) and calculus of variations (Peng *et al.*, 2020) are also used. Dynamic programming (DP) (Zhang and Xiong, 2015) and stochastic dynamic programming (Leroy *et al.*, 2014) (SDP) are two computational techniques used in optimization problems. DP is an approach that deconstructs a complicated problem into smaller subproblems, solving each one recursively. Conversely, SDP integrates a layer of uncertainty and randomness into the decision-making process. These techniques have been extensively studied and applied in various fields. These solutions necessitate familiarity with the complete load profiles, leading to the need for extensive data calculations. The development of online approaches is guided by the changes in the objective function value, which bolsters their durability and performance. In this context, the equivalent-consumption-minimization-strategy (ECMS) as outlined by (Lei *et al.*, 2020). The use of real-time strategies is necessarily less than optimum. ECMS is a result of the application of optimum control philosophy. As stated by Serrao *et al.* (2009), the ECMS is developed and showcased using the PMP technique as its foundation. The analogous factor fulfills a function akin to the co-state in the PMP approach. The offline optimization challenge can be optimally resolved through PMP technique. Also, the offline optimization problem can be optimally solved using ECMS with a constant co-state (Zheng *et al.*, 2014). The external energy maximization strategy (EEMS) outlined by Dhifli *et al.* (2020). By optimizing the utilization of both the SC and the battery, the EEMS system strives to enhance power output, hence resulting in an implicit enhancement in the total system efficiency. Moreover, the FC maintains a consistent state with restricted movement, delivering power exclusively to fulfill demand. The battery and SC act as the key sources for managing transient loads. Thus, this will improve the system's efficiency. Numerous studies have confirmed that the integration of metaheuristic algorithms (MAs) with online EMSs can achieve optimal results. Nevertheless, the application of these algorithms in engineering has experienced significant expansion. In the field of engineering applications, these algorithms have been exceedingly popular (Antarasee *et al.*, 2022). An enhanced version of ECMS and EEMS has been introduced by Rezk *et al.* (2021). This version employs two metaheuristic optimizers, the salp swarm algorithm (SSA) and the mine blast algorithm (MBA), to conduct the optimization process. Merging the SSA with the EEMS leads to peak efficiency and enhanced fuel consumption performance. Using a number of meta-heuristic optimization methods, including an artificial bee colony optimization algorithm (ABC) and a whale optimization algorithm (WOA), Zhao *et al.* (2019) performed a comparison analysis. The findings obtained in this study indicate that the optimized EEMS utilizing the Grey Wolf optimizer (GWO) surpasses the ECMS and its optimized variants. In order to enhance fuel efficiency, a genetic fuzzy-based EMS was suggested by Ahmadi *et al.* (2018). Utilizing a genetic algorithm, an optimized EMS was

developed, as detailed by Lü *et al.* (2020). An approach for managing a hybrid storage system that combines batteries and supercapacitors. The battery energy storage (BES) system demonstrated advantages in preserving the battery state of charge (SoC). An optimized EMS was proposed using a salp swarm algorithm, as outlined by Ghadbane *et al.* (2024). Although various optimization algorithms such as Harris hawks optimization (HHO), PSO, and manta ray foraging optimization (MRFO). The application of MRFO methods aims to optimize energy management in hydrogen fuel cell systems, yet these approaches often face drawbacks, including poor convergence performance, a high sensitivity to parameter settings, and limited flexibility in response to different driving conditions (Rezk *et al.*, 2023). Furthermore, many existing methods focus primarily on minimizing hydrogen consumption without simultaneously optimizing system efficiency and overall performance metrics. In response to these deficiencies, the current study proposes an ECMS-based Aquila optimization algorithm system that flexibly adjusts to changing operating conditions. This system achieves considerable reductions in hydrogen consumption, increases system efficiency, and improves overall performance relative to standard optimization techniques. The main goal of this study is to minimize hydrogen usage to improve the performance of the entire power system, capitalizing on the remarkable effectiveness of the Aquila optimizer, while introducing the application of this algorithm to this specific domain for the first time. The actual application of this technology can improve the driving experience of electric vehicles by increasing their range with more efficient fuel usage and higher energy efficiency. To assess the performance and efficiency of the proposed EMS, the resulting fuel consumption and the associated system's efficiency have been compared to the results of other competitive MAs such as equilibrium optimizer (EO) (Faramarzi *et al.*, 2020), GWO (Mirjalili *et al.*, 2014), RIME-based optimization (RIME) (Su *et al.*, 2023), rain optimization algorithm (ROA) (Moazzeni and Khamehchi, 2020), Northern Goshawk optimization (NGO) (Dehghani *et al.*, 2021), Multi-verse optimizer(MVO) (Mirjalili *et al.*, 2016), White Shark optimizer (WSO) (Braik *et al.*, 2022), and Leopard Seal optimization (LSO) (Rabie *et al.*, 2023). This study's main focus is on developing an improved version of the standard ECMS, which is designed to greatly decrease fuel usage while boosting electrical efficiency. This study aims to accomplish the following primary objectives: 1) Develop a state-of-the-art power management system for FCEVs that maximizes electrical efficiency, reduces fuel consumption, and achieves optimal power distribution. 2) The proposed EMS is accompanied with the Aquila optimizer (AO) to ECMS. This study has been carried out in Saudi Arabia in 2025.

MATERIALS AND METHODS

Architecture for FCEVs

The FCEV generates its power from several components, including a lithium-ion battery, energy storage devices built around supercapacitors, and the main source of energy, a proton exchange membrane fuel cell (PEMFC) (Fig. 1). A DC/DC boost converter that can only go in one direction links the fuel cell to the DC connection. The connection of the battery is established through a bidirectional DC/DC boost converter, with the DC bus directly linked to the SC. In contrast, a bidirectional DC/AC converter powers the vehicle's motor in both traction and braking modes, facilitating current flow in both directions between the DC bus to the motor.

Model for vehicle traction

Here's a guide on how to calculate the traction force by examining the physical forces that affect the vehicle's body, as described in Eq. 1 (Eddine *et al.*, 2022a):

$$F_t = F_a + F_r + F_{acc} + F_{gr} \tag{1}$$

The variables F_a, F_r, F_{acc}, and F_{gr} represent the aerodynamic force, rolling resistance force, acceleration force, and resistance force, respectively. The following definitions are assigned to these forces, using Eq. 2 (Eddine *et al.*, 2022a):

$$\begin{cases} F_a = 0.5\,\xi\, C_d\, A_f\, (v \pm v_w)^2 \\ F_r = m_v\, g\, \mu \\ F_{acc} = \pm k_m\, m_v \dfrac{dv}{dt} \\ F_{gr} = \pm m_v\, g \sin\alpha \end{cases} \tag{2}$$

Following is a list of the variables used in the

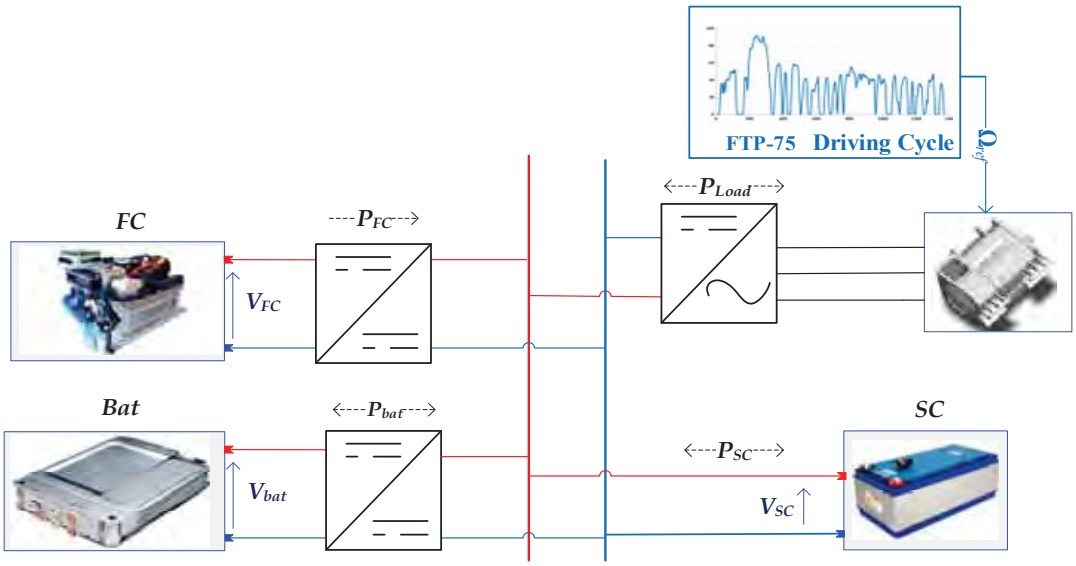


Fig. 1: The structure of the HPS for FHEV

equation: Here, v stands for the vehicle's speed in (m/s), v_w for the wind speed in (m/s), and α for the slope angle in rad. Also, where m_v is the vehicle's mass in kg, and g is the Earth's gravitational acceleration in (m/s^2). ξ denotes the air density in (kg/m^3), and μ stands for the tire's rolling resistance coefficient, which ranges from 0.015 to 0.3. A_f denotes the vehicle's frontal area in (m^2), and C_d varies from 0.2 to 0.4 as the coefficient of aerodynamic drag. k_m signifies the rotational inertia coefficient, which ranges from 1.08 to 1.1.

Hydrogen consumption model for FCs

The FC is an electrochemical device that uses the chemical energy of oxygen and hydrogen to generate electricity. The following relationship exists between the FC output current and hydrogen consumption, using Eq. 3 (Li *et al.*, 2019):

$$C_{H_2}\int_0^t \frac{m_{H_2} n_{cell}}{2F} i_{FC}(t)\,dt \tag{3}$$

The variable C_{H2} represents the rate at which hydrogen is consumed in (g/s). The variable n_{cell} represents the number of cells. m_{H2} represents the molar mass of hydrogen, which is 2.02 (g/mol). i_{FC} represents the output current of the fuel cell in amperes (A). *F* represents the Faraday constant, which is 96,487 coulombs (C).

Model for estimating the SoC in batteries

Model for estimating the SoC in batteries suggests that the SoC of a battery can be computed using Eq. 4 (Ghadbane *et al.*, 2024d):

$$SOC(t) = SOCi - \frac{1}{Q}\int i_{bat}\,dt \tag{4}$$

Where, SOC_i denotes the initial SoC of the battery.

The suggested approach for energy management

The energy management strategy was created with the key objectives of boosting efficiency, lengthening the operational life of batteries and supercapacitors, and decreasing fuel consumption.

Outlining the Issue

Reducing hydrogen consumption and keeping the battery SoC within allowed values are two goals of the ECMS. The ECMS seeks to optimize the power supply by fully leveraging the capabilities of the bus capacitor and battery, as outlined in Eq. 5 (Ghadbane *et al.*, 2024d):

$$f_{obj} = \min\left(\Delta T.P_{bat} + \frac{C_{bus}.v^2}{2}\right) \tag{5}$$

in which ΔT denotes the sample time, v stands for the charge/discharge voltage, P_{bat} denotes the battery power supplied at ΔT, and C_{bus} is the DC bus supercapacitor capacitance. The energy provided by the battery, contingent upon its system on a chip, imposes limitations on this function through an inequality framework. This can be articulated as shown in Eq. 6 (Ghadbane *et al.*, 2024d):

$$P_{bat} \le (SoC - SoC_{\min}).V_{bat}.Q_{bat} \quad (6)$$

in which V_{bat} and Q_{bat} denote the nominal voltage and capacity of the battery, respectively, and SoC_{min} denotes the lowest possible level of the battery's SoC.

For the safety of the battery and to enhance power quality, it is important to regulate both the DC bus voltage and the power that is being supplied by the battery. The following is the manner in which these limitations are articulated, using Eq. 7 (Ghadbane *et al.*, 2024d):

$$\begin{aligned} V_{bus}^{\min} - V_{bus} \le v \le V_{bus}^{\max} - V_{bus} \\ P_{bat}^{\min} \le P_{bat} \le P_{bat}^{\max} \end{aligned} \quad (7)$$

In which the minimum and maximum voltages on the DC bus are represented by V_{bus}^{min} and V_{bus}^{max}, respectively.

Aquila optimizer

The AO is a population-based metaheuristic introduced by Abualigah *et al.* (Abualigah *et al.*, 2021). The classical AO follows five key steps:

Step 1: Initialization

During this phase, a variety of recommended random solutions is produced, and the AO parameters are initialized.

Step 2: Expanded Exploration

This stage emulates Aquila's fundamental hunting method, which involves soaring to a great height before executing a vertical plunge. The algorithm searches the space from a high position, represented mathematically by Eq. (8), where $X_1(t+1)$ is the next solution, and $X_{best}(t)$ is the best solution so far, using Eq. 8 (Abualigah *et al.*, 2021):

$$X_1(t+1) = X_{best}(t) \times \left(1 - \frac{t}{T}\right) + \left(X_M(t) - X_{best}(t) \times rand\right) \quad (8)$$

Step 3: Narrowed exploration

In this phase, Aquila engages in a shaped flight, gliding over a short distance while circling its prey. The behavior is mathematically captured in Eq. (9) (Abualigah *et al.*, 2021):

$$\begin{aligned} X_2(t+1) = X_{best}(t) \times Levy(D) + \\ \left(X_R(t) + (y - x) \times rand\right) \end{aligned} \quad (9)$$

Step 4: Expanded exploitation

During this phase, Aquila performs a low-level flight characterized by a gradual increase in the angle of attack, steadily approaching its prey, which can be illustrated by Eq. 10 (Abualigah *et al.*, 2021). Upper Bound (*ub*), Lower Bound (*lb*), and fixed exploitation parameters α and δ are involved.

$$\begin{aligned} X_3(t+1) = \left(X_{best}(t) \times X_M(t)\right) \times \alpha - \\ rand + \left((ub - lb) \times rand + lb\right) \times \delta \end{aligned} \quad (10)$$

Step 5: Narrowed exploitation

The final phase is inspired by Aquila's walk-and-grab attack, known as Narrowed Exploitation, and described in Eq. 11 (Abualigah *et al.*, 2021):

$$\begin{aligned} X_4(t+1) = QF \times X_{best}(t) - \\ \left(G_1 \times X(t) \times rand\right) - \left(G_2 \times Levy(D) + rand \times G_1\right) \end{aligned} \quad (11)$$

The complete AO procedure is outlined in a flowchart as shown in Fig. 2.

RESULTS AND DISCUSSION

Utilizing the MATLAB/Simulink environment, a simulation model has been created to test and validate the performance of each strategy. The components, including sources and converters, are represented by blocks from the SimPowerSystem blocks. The studied EMS was tested on the Driving Cycle FTP-75 to see how well it performed. Motor power and speed profiles for both FTP-75 are shown in Fig. 3.

In the simulations, the battery and supercapacitor were configured using the same set of parameters. There was a voltage of 270 V in the supercapacitor and a battery SoC of 70%. The hydrogen consumption rate in liters per minute is shown in Fig. 4 while Fig. 5 illustrates the H_2 consumption in grams versus

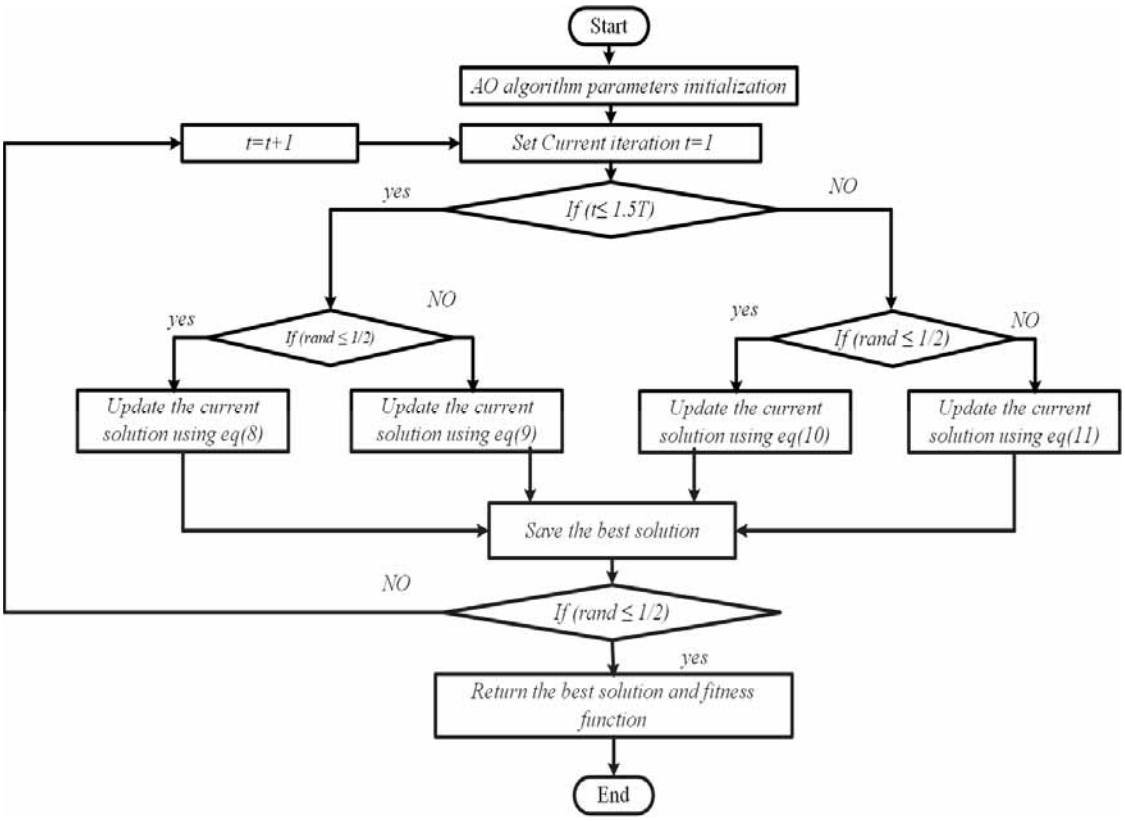


Fig. 2: Aquila optimizer flowchart

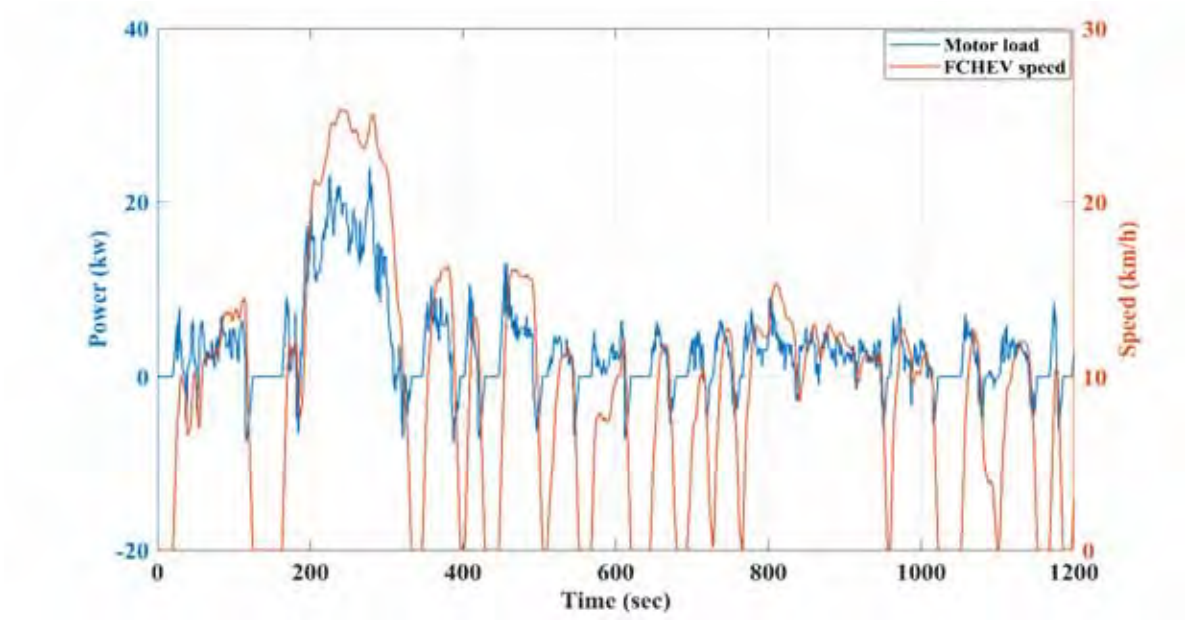


Fig. 3: Power and speed of the FTP-75 driving cycle

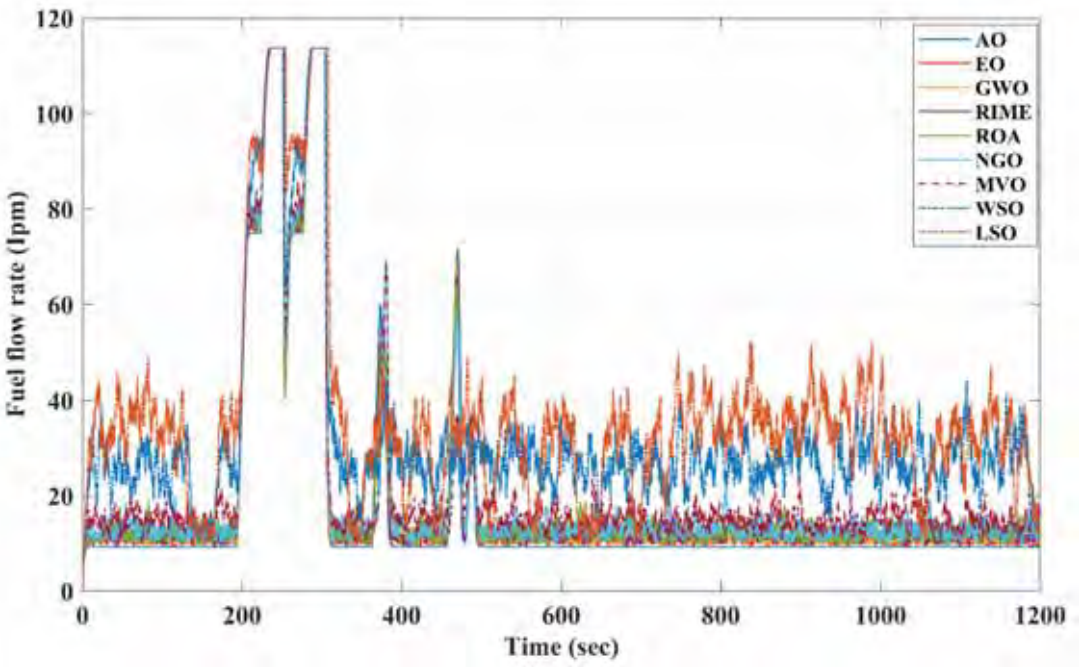


Fig. 4: consumption of hydrogen in (lpm)

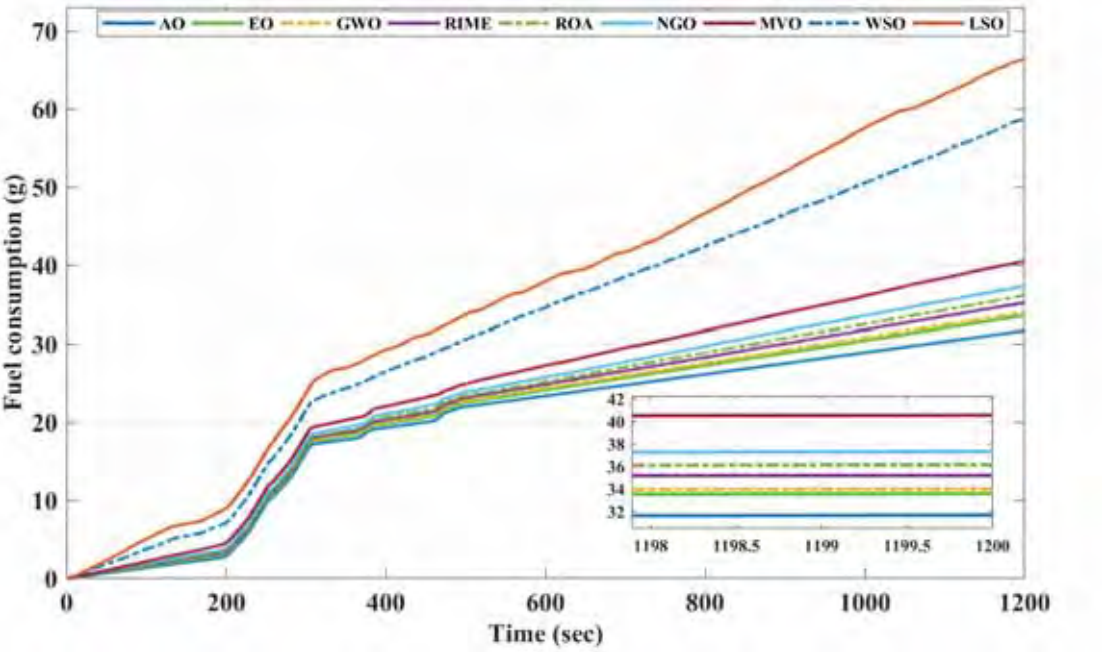


Fig. 5: Consumption of hydrogen (g)

Table 1: Comparative study of several acknowledged EMSs

EMS	Consumed H_2(g)	Efficiency (%)	Final SOC	H_2 Saving (%)	Efficiency 'Increase in h' (%)	Decrease in SoC (%)	Performance Index (%
EO	33.58	56.86	43.96	5.66	0.44	1.79	4.31
GWO	34	56.81	44.32	6.82	0.49	2.15	5.16
RIME	35.22	56.67	45.40	10.05	0.63	3.23	7.45
ROA	36.15	56.69	46.24	12.37	0.61	4.07	8.91
NGO	37.33	56.17	47.23	15.14	1.13	5.06	11.21
MVO	40.56	55.43	50.22	21.89	1.87	8.05	15.71
WSO	58.68	55.41	64.25	46.01	2.89	22.08	26.82
LSO	66.36	54.22	68.93	52.26	3.08	26.76	28.58
AO	31.68	57.3	42.17	0	0	0	0

time in seconds. These statistics reveal that the recommended approach can significantly decrease hydrogen usage and its consumption rate relative to the alternatives being assessed. This recommended strategy may lead to decreased hydrogen utilization and consumption levels relative to alternative methods.

Table 1 presents the comparative results among the several ESMs that were taken into account. The analysis demonstrated that AO based on ECMS is the best solution. The total quantity of hydrogen consumption decreases from 66.36 g (when utilizing the LSO-ECMS) to 31.68 g when the AO based on ECMS is implemented.

To summarize, the utilization of ECMS-based AO revealed considerable advancements relative to alternative control systems, specifically EO, GWO, RIME, ROA, NGO, MVO, WSO, and LSO. Initially, the ECMS-based AO system exhibited noteworthy decreases in hydrogen consumption. The drop was 5.66% compared to EO, 6.82% compared to GWO, 10.05% when measured against RIME, 12.37% compared to ROA, 15.14% in comparison to NGO, 21.89% compared to MVO, 46.01% compared to WSO, and 52.26% compared to LSO. The recommended method utilizing ECMS has proven to lower hydrogen consumption and enhance resource efficiency, highlighted by the substantial reduction in hydrogen usage. Moreover, the application of the ECMS-based AO technique substantially boosts the efficiency of the system. The efficiency enhancement was 0.44% higher than the EO, 0.49% higher than the GWO, 0.63% higher than the RIME, 0.61% higher than the ROA, 1.13% higher than the NGO, 1.87% higher than the MVO, 3.08% higher than the WSO, and 2.89% higher than the LSO. The observed improvements in efficiency indicate that the ECMS-based AO strategy excels in delivering enhanced performance in terms of generating hydrogen-powered systems. Consequently, it yields a more cost-effective and ecologically beneficial system. The ECMS-based AO approach presents certain advantages; however, it is important to evaluate the potential downsides in relation to the battery's SoC. The SoC decreased by 1.79% in comparison to the EO strategy, 2.15% in comparison to the GWO strategy, 3.23% in comparison to the RIME strategy, 4.07% in comparison to the ROA strategy, 5.06% in comparison to the NGO strategy, 8.05% in comparison to the MVO strategy, 22.08% in comparison to the WSO strategy, and 26.76% in comparison to the LSO strategy. Analyzing the decline in SoC is vital, as it can affect not just short-term outcomes but also long-term performance, which is key to maintaining the stability of the hydrogen-based system. The AO technique based on ECMS demonstrated substantial advancement in evaluating the comprehensive performance index. The improvement percentages compared to the EO, GWO, RIME, ROA, NGO, MVO, WSO, and LSO were 4.31%, 5.16 %, 7.45%, 8.91%, 11.21%, 15.71%, 27.08%, and 28.39%, respectively. The study by Rezk *et al.* (2023) employed three optimization techniques: HHO, particle swarm optimization (PSO), and MRFO. Their results during FTP-75 driving cycle

Table 2: Comparative analysis of several regarded EMSs (Rezk *et al.*, 2023)

EMS	Consumed H_2(g)	Efficiency (%)	Final SoC	H_2 Saving (%)	Efficiency Increase in *h*' (%)	Decrease in SoC (%)	Performance Index (%)
HHO	44.78	55.04	58.21	29.25	2.26	16.04	15.470
PSO	59.1	48.7	62.93	46.4	8.6	20.07	34.93
MRFO	63.61	47.17	64.42	50.02	10.13	22.25	37.9

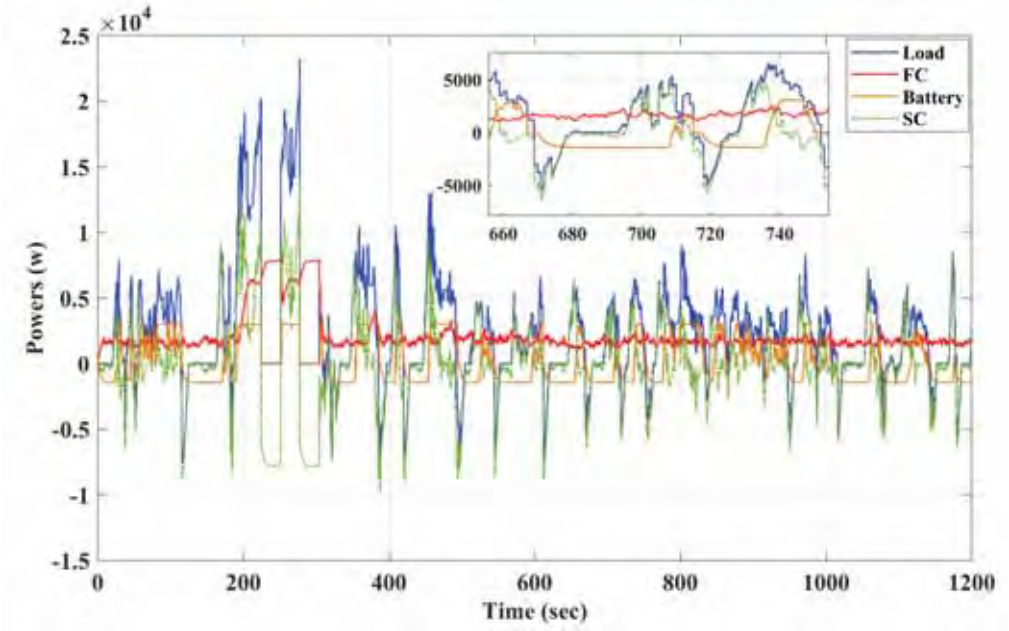


Fig. 6: Load, fuel cell, SC, and battery. power waveforms

confirmed the HHO's superiority. The data presented in Table 2 indicates that the ECMS-based AO system showed remarkable declines in hydrogen usage. The drop was 29.25 % compared to HHO, 46.4 % compared to PSO, and 50.02 % compared to MRFO. Furthermore, the utilization of the ECMS-based AO technique significantly enhances the efficiency of the system. The efficiency enhancement was 2.26% higher than the HHO, 8.6% higher than the PSO, and 10.13% higher than the MRFO. SoC decreased by 16.04% in comparison to the HHO strategy, 20.07% in comparison to the PSO strategy, and 22.25% in comparison to the MRFO strategy. The application of the AO technique with ECMS revealed considerable improvements in the evaluation of the comprehensive performance index. The improvement percentages compared to the HHO, PSO, and MRFO were 15.47%, 34.93%, and 37.9%, respectively.

As it is illustrated in Fig. 6, the FC is responsible for the bulk of the tasks, operating with slower dynamics, whereas the battery's role is to store additional energy for times when the fuel cell's efficiency declines. It may require a significant amount of time for FC to achieve its intended level of productivity. The battery can provide its stored energy when there is a surge in demand or a lack of power, which significantly boosts the system's reliability. Nevertheless, the rapid fluctuations in the load are mitigated by the implementation of a SC. Basically, storing/discharging electrical energy in/from SC usually runs smoothly due to the transient behavior of the capacitor which prevents the voltage on its terminals to change instantaneously.

Fig. 7 illustrates the FC voltage data that

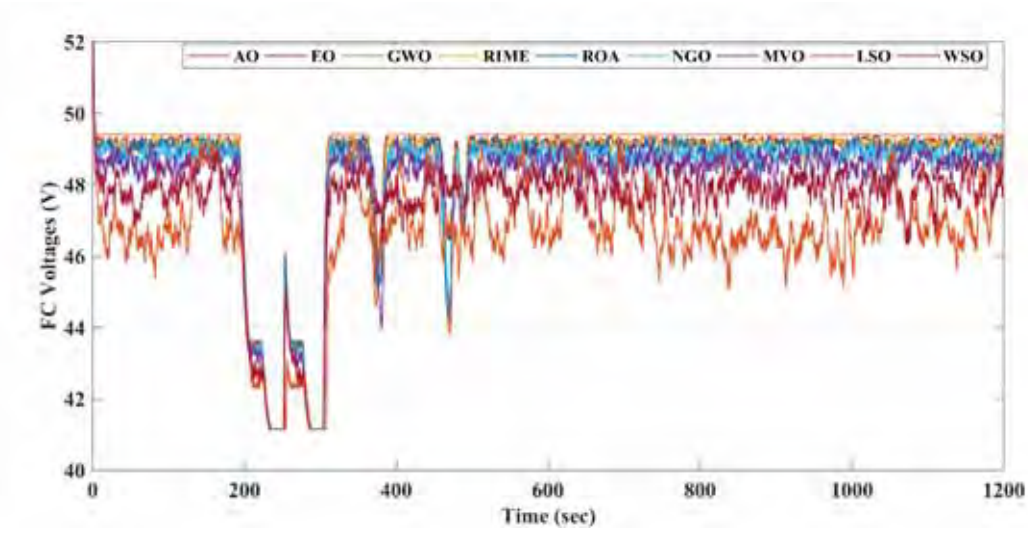


Fig. 7: FC voltage for various EMSs

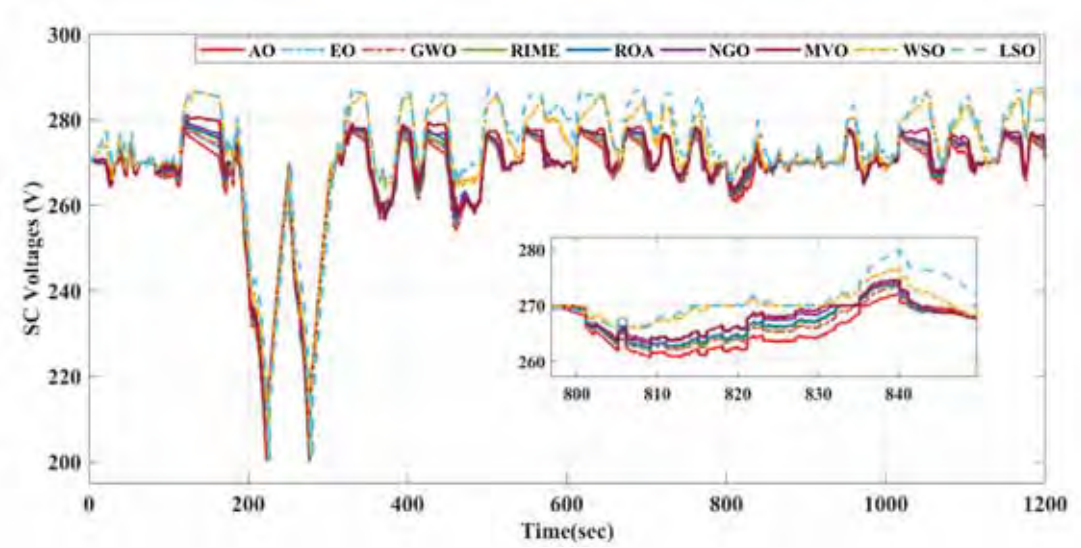


Fig. 8: SC voltage for various EMSs

were acquired from various control schemes. In comparison to alternative methods, the proposed method employs the FC with moderate dynamics. This approach yields a fuel cell characterized by sustained well-being, which subsequently boosts its cost-effectiveness, efficiency, and lifespan.

Fig. 8 shows the voltage of the superconducting circuit (SC). Voltage swings are caused by the changes in power absorption and dissipation occurring in the DC bus. When supply and demand for electricity are balanced, the voltage is 270 V. Nonetheless, the SC voltage swiftly decreases when there are sudden shifts in the load to accommodate the immediate power requirements.

Fig. 9 depicts the voltage of the battery. When following the recommended approach grounded in the AO, the battery voltage shows considerable changes in its levels. This behavior can be understood as a function of the battery system's objective to protect the fuel cell system and limit voltage instability. This results in an increase in the amplitude of voltage variations, as illustrated in the accompanying Fig. 9.

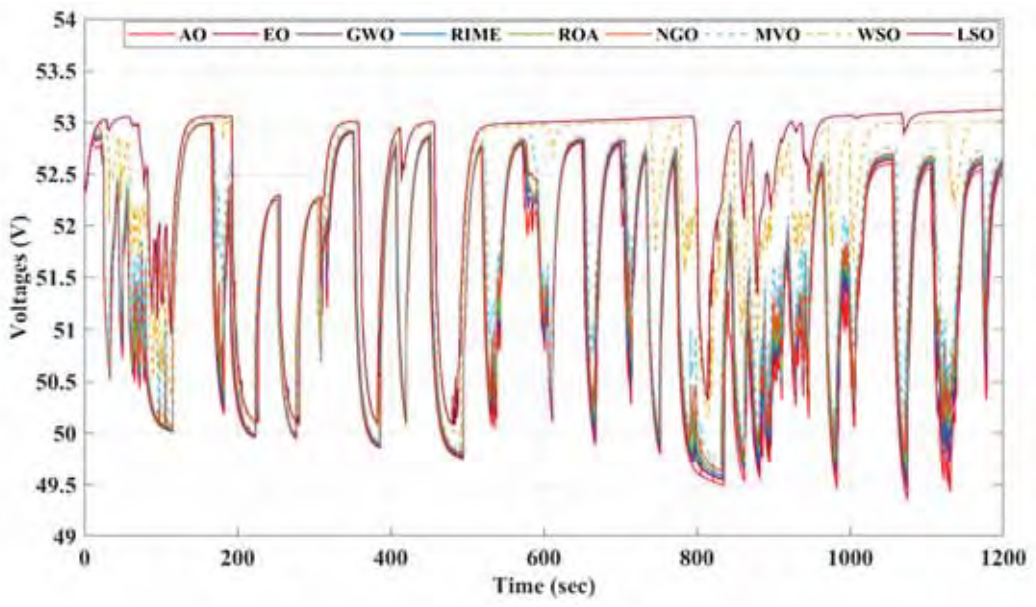


Fig. 9: Battery voltage for various EMS

CONCLUSION

This study introduces an innovative method for achieving an energy-efficient management system, which is implemented in a hybrid fuel cell electric vehicle. The main important contribution of this study is the introduction of an energy management system that utilizes an optimized version of the ECMS with the implementation of the Aquila Optimizer (AO). This novel strategy is designed to boost the fuel economy, performance, and overall effectiveness of HPS employed in fuel-cell electric vehicles. The EMS was evaluated using EO, GWO, RIME, ROA, NGO, MVO, WSO, and LSO. The effectiveness of the electrical systems and fuel economy were examined in a study. The analysis showed that the proposed EMS significantly lowered fuel consumption by 52.26%. Moreover, there was a 3.08% enhancement in overall efficiency. The objective of this study is to lower fuel consumption in order to increase the performance of the entire power system. The researchers intend to delve into the complicated matter of multi-optimization, which is influenced by the nuanced characteristics of the battery's SoC. Moreover, the assessment of the lost power would also be crucial in enhancing the system's efficiency. Besides contributing to fuel savings and efficiency gains, the proposed EMS is key to lowering the environmental footprint. The strategy of minimizing hydrogen consumption indirectly lessens the reliance on hydrogen production, which can result in varying environmental effects depending on the methods employed for production. As FCEVs emerge as a promising alternative to traditional internal combustion engine vehicles, optimizing energy management systems is a key step toward making these vehicles more viable for widespread adoption. Despite these promising advancements, some challenges remain. One of the primary limitations of the proposed approach is its real-time implementation feasibility. The AO algorithm requires substantial computational resources, making real-world applications dependent on advanced, high-speed processors. It is expected that the steady evolution of computing technologies and embedded systems will help address this challenge, facilitating the real-time implementation of the optimization process. Several research directions can be pursued to further enhance the proposed EMS and address existing challenges. Future work will focus on improving the real-time implementation of the AO-based optimization strategy by developing more efficient and computationally adaptive algorithms. Furthermore, an extensive multi-objective optimization framework will be investigated, which will integrate battery

state of charge management with considerations for fuel efficiency and overall system performance. Since SoC depletion was identified as a crucial factor affecting long-term system stability, future studies will investigate advanced control techniques to maintain an optimal charge balance and extend battery lifespan. A significant focus for future studies should be the comprehensive examination of power losses occurring within the system. Understanding and mitigating these losses will be essential in further improving overall system efficiency. Investigating hybrid energy storage solutions. Furthermore, prioritizing real-world experimental validation of the suggested EMS in diverse driving scenarios will be crucial for determining its practical utility and durability. Ultimately, by addressing these challenges and further refining the EMS, current study aims to contribute to the development of more efficient, cost-effective, and environmentally sustainable FCEVs, paving the way for broader adoption of clean energy transportation solutions. For instance, adaptive learning algorithms allow the system to fine-tune the optimization process in real time, improving both convergence speed and computational efficiency while maintaining optimal performance. Upcoming studies will focus on integrating Vehicle-to-Grid and smart grid technologies within the existing EMS framework, analyzing their technical and economic consequences. Enhancing the optimization algorithm to account for real-time grid conditions, energy prices, and dynamic grid needs will further maximize system efficiency and support a more resilient and sustainable energy ecosystem.

RESEARCH GAP

Optimization techniques like Harris Hawks Optimizer and Manta ray foraging optimization have been widely explored for hydrogen consumption, but there is limited research on Aquila optimization algorithm. This study fills the existing gap by showcasing the enhanced effectiveness of the energy management-based AO technique in minimizing hydrogen usage and improving system efficiency when compared to HHO and MRFO. The research findings will offer new insights into optimization strategies for sustainable energy systems.

AUTHOR CONTRIBUTIONS

A.M. Nassef, as the corresponding author, has contributed the research proposal making, built the simulation model, and writing the manuscript, H.E. Ghadbane participated in the preparation of manuscript, performed results analysis, and optimization process using MHs. E.T. Sayed helped in drawing the figures and drafting the manuscript, H. Rezk helped in building the MATLAB Simulink model, drafting the manuscript, results' analysis, and tabulation of the results.

ACKNOWLEDGEMENT

The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number [PSAU/2024/01/32088].

CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
A	Amperes
ABC	Artificial bee colony optimization algorithm
AC	Alternating current
AO	Aquila optimizer
BES	Battery energy storage
C	Coulombs
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COP	Conference of Parties
DC	Direct current
DP	Dynamic programming
ECMS	Equivalent consumption minimization strategy
EEMS	Enhanced efficient energy management system
EMS	Efficient energy management system
EO	Equilibrium optimizer
ESS	Energy storage system
EVs	Electric vehicles
FC	Fuel cells
FCEV	Fuel cell hybrid electric vehicle
FTP	Federal test procedure
g	Gram
GWO	Grey wolf optimizer
H_2	Hydrogen
HHO	Harris hawks optimization
kg	Kilogram
lb	Lower bound
lpm	Liters per minute
LSO	Leopard seal optimization
m	Meters
m/s	Meters per second
MAs	Metaheuristic algorithms
MBA	Mine blast algorithm
MFCs	Microbial fuel cells
MKCl	Molar potassium chloride
MRFO	Manta ray foraging optimization
MVO	Multi-verse Optimizer
NGO	Northern goshawk optimization
^oC	Degree celsius
PEMFC	Proton exchange membrane fuel cell
PMP	Pontryagin's maximal principle
PSO	Particle swarm optimization
RIME	RIME-based Optimization
ROA	Rain optimization algorithm
SC	Supercapacitor
SDP	Stochastic dynamic programming
SoC	State-of-charge
SSA	Salp swarm algorithm
ub	Upper bound
UK	United Kingdom
V	Volts
WOA	Whale optimization algorithm
WSO	White shark optimizer

REFERENCES

Abualigah, L.; Yousri, D.; Abd Elaziz, M.; Ewees, A.A.; Al-qaness, M. A.A.; Gandomi, A.H., (2021). Aquila Optimizer: A novel meta-heuristic optimization algorithm. Comput. Ind. Eng., 157: 107250 **(37 pages).**

Ahmadi, S.; Bathaee, S.M.T.; Hosseinpour, A.H., (2018). Improving fuel economy and performance of a fuel-cell hybrid electric vehicle (fuel-cell, battery, and ultra-capacitor) using optimized energy management strategy. Energy Convers. Manage., 160: 74-84 **(11 pages).**

Antarasee, P.; Premrudeepreechacharn, S.; Siritaratiwat, A.; Khunkitti, S., (2022). Optimal design of electric vehicle fast-charging station's structure using metaheuristic algorithms. Sustainability. 15(1): 771 **(22 pages).**

Arat, H.T., (2019). Alternative fuelled hybrid electric vehicle (AF-HEV) with hydrogen enriched internal combustion engine. Int. J. Hydrogen Energy. 44(34): 19005-19016 **(12 pages).**

Bauer, S.; Suchaneck, A.; Puente León, F., (2014). Thermal and energy battery management optimization in electric vehicles using Pontryagin's maximum principle. J. Power Sources. 246: 808-818 **(11 pages).**

Braik, M.; Hammouri, A.; Atwan, J.; Al-Betar, M.A.; Awadallah, M.A., (2022). White Shark Optimizer: A novel bio-inspired meta-heuristic algorithm for global optimization problems. Knowl. -Based Syst., 243: 108457-108457 **(19 pages).**

Changizian, S.; Ahmadi, P.; Raeesi, M.; Javani, N., (2020). Performance optimization of hybrid hydrogen fuel cell-electric vehicles in real driving cycles. Int. J. Hydrogen Energy. 45(60): 35180-35197 **(18 pages).**

Dehghani, M., Hubalovsky, S.; Trojovsky, P., (2021). Northern Goshawk Optimization: A new swarm-based algorithm for

solving optimization problems. IEEE Access, 9: 162059-162080 **(22 pages).**

Dhifli, M.; Lashab, A.; Guerrero, J. M.; Abusorrah, A.; Al-Turki, Y.A.; Cherif, A., (2020). Enhanced intelligent energy management system for a renewable energy-based AC microgrid. Energies. 13(12) **(17 pages).**

Djerioui, A.; Houari, A.; Zeghlache, S.; Saim, A; Benkhoris, M. F; Mesbahi, T; Machmoum, M., (2019). Energy management strategy of Supercapacitor/Fuel Cell energy storage devices for vehicle applications. Int. J. Hydrogen Energy. 44(41): 23416-23428 **(24 pages).**

Eddine, G.H.; Said, B.; Houari, A.; Dieroui, A.; Mesbahi, T., (2022). integral sliding mode control of synchronous reluctance machine based electric vehicle powered by battery/supercapacitor hybrid source. 2022 19th International Multi-Conference on Systems, Signals and Devices (SSD): 2133-2138 (**6 pages).**

Eddine, G.H.; Said, B.; Houari, A.; Djeroui, A.; Mesbahi, T.; Abdelhak, H., (2022). Energy Management Strategy for Hybrid Power System Implemented with Processor in the Loop. 2022 IEEE International Conference on Electrical Sciences and Technologies in Maghreb, CISTEM 2022 (**6 pages).**

Faramarzi, A.; Heidarinejad, M.; Stephens, B.; Mirjalili, S., (2020). Equilibrium optimizer: A novel optimization algorithm. Knowl.-Based Syst., 191: 105190-105190 **(21 pages).**

Ghadbane, H.E.; Barkat, S.; Djerioui, A.; Houari, A.; Oproescu, M.; Bizon, N., (2024). Energy management of electric vehicle using a new strategy based on slap swarm optimization and differential flatness control. Sci. Rep., 14(1): 3629 **(19 pages).**

Ghadbane, H.E.; Barkat, S.; Houari, A.; Djerioui, A.; Abdelhak, H.; Mesbahi, T., (2024). A load following energy management strategy for a battery-supercapacitor hybrid power system implemented with a PIL co-simulation approach. Smart Grids Sustainable Energy. 9(2): 1-15 **(15 pages).**

Ghadbane, H.E.; Barkat, S.; Houari, A.; Djerioui, A.; Rezk, H.; Louzazni, M.; Palanisamy, R., (2024). Optimal adaptive fractional order integral sliding mode controller-energy management strategy for electric vehicles based on bald eagle search algorithm. Int. J. Energy Res., 2024(1) **(22 pages).**

Ghadbane, H.E.; Barkat, S.; Houari, A.; Ferahtia, S.; Djerioui, A.; Mesbahi, T., (2024). A new energy management strategy for electric vehicles based on optimal adaptive state machine control. Smart Grids Sustainable Energy. 9(2) **(15 pages).**

Ghadbane, H.E.; Rezk, H.; Ferahtia, S.; Barkat, S.; Al-Dhaifallah, M., (2024). Optimal parameter identification strategy applied to lithium-ion battery model for electric vehicles using drive cycle data. Energy. 11: 2049-2058 **(10 pages).**

Hidayat, W.; Wijaya, B.A.; Saputra, B.; Rani, I.T.; Kim, S.; Lee, S.; Yoo, J.; Park, B.B.; Suryanegara, L.; Lubis, M.A.R., (2024). Torrefaction of bamboo pellets using a fixed counterflow multibaffle reactor for renewable energy applications. Global J. Environ. Sci. Manage., 10(1), 169-188 **(20 pages)**.

Lei, Z.; Qin, D.; Hou, L.; Peng, J.; Liu, Y.; Chen, Z., (2020). An adaptive equivalent consumption minimization strategy for plug-in hybrid electric vehicles based on traffic information. Energy. 190: 116409-116409 **(13 pages).**

Leroy, T.; Vidal-Naquet, F.; Tona, P., (2014). Stochastic dynamic programming based energy management of HEV's: An experimental validation. IFAC Proceedings. 47(3): 4813-4818 **(6 pages).**

Li, H.; Ravey, A.; N'Diaye, A.; Djerdir, A., (2019). Online adaptive equivalent consumption minimization strategy for fuel cell hybrid electric vehicle considering power sources degradation. Energy Convers. Manage., 192: 133-149 **(17 pages).**

Lü, X.; Wu, Y.; Lian, J.; Zhang, Y.; Chen, C.; Wang, P.; Meng, L., (2020). Energy management of hybrid electric vehicles: A review of energy optimization of fuel cell hybrid power system based on genetic algorithm. Energy Convers. Manage., 205: 112474-112474 **(26 pages).**

Mirjalili, S.; Mirjalili, S.M.; Hatamlou, A., (2016). Multi-Verse Optimizer: a nature-inspired algorithm for global optimization. Neural Comput. Appl., 27(2): 495-513 **(19 pages).**

Mirjalili, S.; Mirjalili, S.M.; Lewis, A., (2014). Grey Wolf Optimizer. Adv. Eng. Softw., 69: 46-61 **(16 pages).**

Moazzeni, A.R.; Khamehchi, E., (2020). Rain optimization algorithm (ROA): A new metaheuristic method for drilling optimization solutions. J. Pet. Sci. Eng., 195: 107512-107512 **(13 pages).**

Nassef, A.M.; Houssein, E.H.; Rezk, H.; Fathy, A., (2023). Optimal allocation of biomass distributed generators using modified hunger games search to reduce CO_2 emissions. J. Mar. Sci. Eng., 11(2) **(23 pages).**

Nazari-Heris, M.; Abapour, M.; Mohammadi-Ivatloo, B., (2022). An Updated Review and Outlook on Electric Vehicle Aggregators in Electric Energy Networks. Sustainability. 14(23), 15747-15747 **(24 pages).**

Payakkamas, P.; de Kraker, J.; Dijk, M., (2023). Transformation of the Urban Energy–Mobility Nexus: Implications for Sustainability and Equity. Sustainability. 15(2): 1328-1328 **(17 pages).**

Peng, H.; Li, J.; Löwenstein, L.; Hameyer, K., (2020). A scalable, causal, adaptive energy management strategy based on optimal control theory for a fuel cell hybrid railway vehicle. Appl. Energy. 267 **(17 pages).**

Rabie, A.H.; Mansour, N.A.; Saleh, A.I., (2023). Leopard seal optimization (LSO): A natural inspired meta-heuristic algorithm. Commun. Nonlinear Sci. Numer. Simul. 125: 107338-107338 **(32 pages).**

Rahman, A.U.; Zehra, S.S.; Ahmad, I.; Armghan, H., (2021). Fuzzy supertwisting sliding mode-based energy management and control of hybrid energy storage system in electric vehicle considering fuel economy. J. Energy Storage. 37: 102468-102468 **(14 pages).**

Ramli, M.; Mardlijah, M.; Ikhwan, M.; Umam, K., (2022). Fuzzy entropy type II method for optimizing clean and renewable solar energy. Global J. Environ. Sci. Manage., 8(3): 389-402 **(14 pages).**

Rashif, M.N.; Hartini, S.; Sari, D.P.; Ramadan, B.S.; Matsumoto, T.; Balasbaneh, A.T., (2025). Life cycle assessment of biomass waste briquettes as renewable energy. Global J. Environ. Sci. Manage., 11(1): 207-224 **(18 pages).**

Rezk, H.; Abdelkareem, M.A.; Alshathri, S.I.; Sayed, E.T.; Ramadan, M.; Olabi, A.G., (2023). Fuel economy energy management of electric vehicles using harris hawks Optimization. Sustainability. 15(16): 12424-12424 **(15 pages).**

Rezk, H.; Nassef, A.M.; Abdelkareem, M.A.; Alami, A.H.; Fathy, A., (2021). Comparison among various energy management strategies for reducing hydrogen consumption in a hybrid fuel cell/supercapacitor/battery system. Int. J. Hydrogen Energy. 46(8): 6110-6126 **(17 pages).**

Santoso, A.D.; Daulay, H.; Priyanti, A.; Silalahi, M.; Yaumidin, U.K.; Irawati, N.; Sumartono, H.; Astuti, P.; Farandy, A.R.; Parikesit,

A.; Manti, M.F.; Indriasari, E.; Joelijani, W.; Wahyuni, S., (2024). Conversion of motorcycles to electric vehicles towards sustainable mobility. Global J. Environ. Sci. Manage., 10(SI): 181-200 **(20 pages).**

Serrao, L; Onori, S.; Rizzoni, G., (2009). ECMS as a realization of pontryagin's minimum principle for HEV control. Proceeding of American Control Conference. 3964-3969 **(6 pages).**

Sivakumar, D. (2020). Pollution reduction and electricity production from dairy industry wastewater with microbial fuel cell. Global J. Environ. Sci. Manage., 6(2): 145-164 **(20 pages)**.

Sivakumar, D. (2021). Wastewater treatment and bioelectricity production in microbial fuel cell: salt bridge configurations. Int. J. Environ. Sci. Technol., 18(6): 1379-1394 **(16 pages)**.

Sorlei, I.S.; Bizon, N.; Thounthong, P.; Varlam, M.; Carcadea, E.; Culcer, M.; Iliescu, M.; Raceanu, M., (2021). Fuel cell electric vehicles—A brief review of current topologies and energy management strategies. Energies. 14(1): 252-252 **(30 pages).**

Su, H.; Zhao, D.; Heidari, A.A.; Liu, L.; Zhang, X.; Mafarja, M.; Chen, H., (2023). RIME: A physics-based optimization. Neurocomputing. 532: 183-214 **(32 pages).**

Sulaiman, N.; Hannan, M.A.; Mohamed, A.; Majlan, E.H.; Wan Daud, W. R., (2015). A review on energy management system for fuel cell hybrid electric vehicle: Issues and challenges. Renew. Sustainable Energy Rev., 52: 802-814 **(13 pages).**

Veziroglu, A; Macario, R., (2011). Fuel cell vehicles: State of the art with economic and environmental concerns. Int. J. Hydrogen Energy. 36(1): 25-43 **(19 pages).**

Wang, Z.; Luo, W.; Xu, S.; Yan, Y.; Huang, L.; Wang, J.; Hao, W; Yang, Z., (2023). Electric Vehicle Lithium-Ion Battery Fault Diagnosis Based on Multi-Method Fusion of Big Data. Sustainability. 15(2): 1120-1120 **(18 pages).**

York, R; Bell, S.E., (2019). Energy transitions or additions? Energy Res. Soc. Sci., 51, 40-43 **(4 pages).**

Zhang, S.; Xiong, R., (2015). Adaptive energy management of a plug-in hybrid electric vehicle based on driving pattern recognition and dynamic programming. Appl. Energy. 155: 68-78 **(11 pages).**

Zhang, Z.; Guan, C.; Liu, Z., (2020). Real-Time Optimization Energy management strategy for fuel cell hybrid ships considering power sources degradation. IEEE Access. 8: 87046-87059 **(16 pages).**

Zhao, J.; Ramadan, H.S; Becherif, M., (2019). Metaheuristic-based energy management strategies for fuel cell emergency power unit in electrical aircraft. Int. J. Hydrogen Energy. 44(4): 2390-2406 **(17 pages).**

Zheng, C.H; Xu, G.Q; Cha, S.W; Liang, Q., (2014). Numerical comparison of ECMS and PMP-based optimal control strategy in hybrid vehicles. Int. J. Automot. Technol., 15(7): 1189-1196 **(8 pages).**

AUTHOR (S) BIOSKETCHES

Nassef, A.M., Ph.D., Associate Professor, Department of Electrical Engineering, College of Engineering in Wadi Alddawasir, Prince Sattam bin Abdulaziz University, Wadi Alddawasir, Saudi Arabia.
- Email: *a.nasef@psau.edu.sa*
- ORCID: 0000-0001-9604-5737
- Web of Science ResearcherID: Q-5076-2019
- Scopus Author ID: 56736102900
- Homepage: https://www.scopus.com/authid/detail.uri?authorId=56736102900

Ghadbane, H.E., Ph.D. Candidate, Département d'Electrotechnique et Automatique, Laboratoire de Génie Électrique de Guelma, Université 8 Mai 1945, Guelma, Algeria.
- Email: *ghadbane.houssameddine@univ-guelma.dz*
- ORCID: 0000-0001-8674-9853
- Web of Science ResearcherID: KDU-6866-2024
- Scopus Author ID: 58863723500
- Homepage: https://www.scopus.com/authid/detail.uri?authorId=58863723500

Sayed, E.T., Ph.D., Professor, Chemical Engineering Department, Faculty of Engineering, Minia University, Egypt.
- Email: e.kasem@mu.edu.eg
- ORCID: 0000-0002-0759-4484
- Web of Science ResearcherID: AEE-4547-2022
- Scopus Author ID: 54985478800
- Homepage: https://scholar.google.com.eg/citations?user=03qdJdsAAAAJ&hl=en

Rezk, H., Ph.D., Associate Professor, Department of Electrical Engineering, College of Engineering in Wadi Alddawasir, Prince Sattam bin Abdulaziz University, Wadi Alddawasir, Saudi Arabia.
- Email: *hr.hussien@psau.edu.sa*
- ORCID: 0000-0001-9254-2744
- Web of Science ResearcherID: M-2100-2019
- Scopus Author ID: 55425573200
- Homepage: https://scholar.google.com.eg/citations?user=R0pThmwAAAAJ&hl=en

HOW TO CITE THIS ARTICLE

Nassef, A.M.; Ghadbane, H.E.; Sayed, E.T.; Rezk, H., (2025). Reducing hydrogen consumption in hybrid electric vehicles using Aquila optimization algorithm.
Global J. Environ. Sci. Manage., 11(2): 695-710.

DOI: 10.22034/gjesm.2025.02.18

URL: https://www.gjesm.net/article_722284.html



Global J. Environ. Sci. Manage. 11(2): 711-732, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Morphological and molecular monitoring of fishes in the waters of mangrove ecosystems

M. Basyuni[1,2,*], Irmawati[3], A. Mubaraq[1,5], A. Susilowati[1,2], A.B. Rangkuti[1,2], Desrita[1,4], A.A. Aznawi[1,5], S.S. Al Mustaniroh[1], S.H. Larekeng[6], A.H. Salman[6], E.R. Ardli[7], Y. Isowa[8], T. Kajita[8]

[1] *Center of Excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia*

[2] *Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Medan 20155, Indonesia*

[3] *Faculty of Marine Science and Fisheries, Universitas Hasanuddin, Makassar 90245, Indonesia*

[4] *Department of Aquatic Resources Management, Faculty of Agriculture, Universitas Sumatera Utara, Medan 20155, Indonesia*

[5] *Doctoral Program of Agriculture Science, Faculty of Agriculture, Universitas Sumatera Utara, Medan 20155, Indonesia*

[6] *Biotechnology and Tree Breeding Laboratory, Faculty of Forestry, Universitas Hasanuddin, Makassar 90245, Indonesia*

[7] *Faculty of Biology, Jendral Soedirman University, Purwokerto 53122, Indonesia*

[8] *Iriomote Station, Tropical Biosphere Research Center, University of the Ryukyus, Taketomi, Okinawa 907-1541, Japan*

ARTICLE INFO

Article History:
Received 01 November 2024
Revised 05 January 2025
Accepted 12 March 2025

Keywords:
Deoxyribonucleic acid (DNA)
Endangered
Fish communities
Morphological conservation
Ribosomal ribonucleic acid (rRNA)

ABSTRACT

BACKGROUND AND OBJECTIVES: Mangroves are primarily found along Sumatra's east coast in Aceh and North Sumatra, Indonesia. Fish communities and other marine life are supported by mangrove forests, which are extremely productive ecosystems. This study used morphological and 16 small subunit ribosomal ribonucleid acid barcodes to track fish diversity in waters surrounding mangroves. The study objectives were to integrate morphological identification with 16 small subunit ribosomal ribonucleic acid deoxyribonucleic acid barcoding to assess fish diversity in mangrove ecosystems along the east coast of North Sumatra and Aceh, Indonesia.

METHODS: Study sites were selected in five locations, namely, Percut Sei Tuan, Belawan, Lubuk Kertang, and Pulau Sembilan in Sumatera Utara coast and Langsa in Aceh coast. Fish specimens were caught using gillnet and danish seines operated by the local fishermen. Morphological identification was performed based on standard taxonomic keys, and deoxyribonucleic acid barcoding using 16 small subunit ribosomal ribonucleic acid deoxyribonucleic acid marker was applied to validate species identification.

FINDINGS: Seventy fish specimens were 70 collected, and 62 species and 39 families were morphologically identified. *Leiognathus equula (Leiognathidae)* was found in all study sites, followed by *Ambassis vachellii (Ambassidae)*, *Pomadasys argenteus (Haemulidae)*, and *Eleutheronema tetradactylum (Polynemidae)* in four locations. *Gerres filamentosus (Gerreidae)*, *Terapon jarbua (Teraponidae)*, *Sphyraena qenie (Spyraenoidae)*, and *Elops machnata (Elopidae)* were detected in three locations. ribosomal ribonucleic acid barcoding confirmed 17 of the fish species detected. Deoxyribonucleic acid barcoding using 16 small subunit ribosomal ribonucleic acid validated the identification of 17 species, confirming that morphological and molecular approaches are complementary in assessing fish diversity. *Two species, Larimichthys crocea and Thunnus maccoyii, were found to be critically endangered and endangered, respectively*.

CONCLUSION: The combination of field surveys and 16 small subunit ribosomal ribonucleic acid barcoding provides a comprehensive assessment of the changes in fish species composition and abundance over time, allowing for the identification of vulnerable species and the development of effective conservation strategies. The findings highlight the importance of long-term monitoring, habitat conservation, and sustainable fisheries management to protect fish biodiversity in mangrove ecosystems along the east coast of North Sumatra and Aceh.

DOI: 10.22034/gjesm.2025.02.19

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
71

NUMBER OF FIGURES
9

NUMBER OF TABLES
3

*Corresponding Author:
Email: *m.basyuni@usu.ac.id*
Phone: +62853 2577 6785
ORCID: 0000-0003-1120-8571

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Mangrove forests are highly dynamic intertidal ecosystems that support marine biodiversity. These habitats serve as breeding, nursery, and feeding grounds for various fish species, contributing substantially to fisheries and coastal livelihoods (Basyuni *et al.,* 2021; Fekri *et al.,* 2024). Many animals and microorganisms, such as fishes, shrimps, and macrozoobenthos, are closely associated with mangrove ecosystems (Basyuni *et al.,* 2021; Sari *et al.,* 2022). With fisheries and aquaculture becoming key sectors in its regional and national economic development, Indonesia now accounts for approximately 8 percent (%) of global fish production (FAO, 2024). As one of the world's largest archipelagic nations, this country hosts extensive mangrove forests, particularly along the east coast of North Sumatra and Aceh. Despite their ecological and economic importance, mangrove ecosystems are increasingly threatened by anthropogenic activities, such as deforestation, pollution, and overfishing. These disturbances can lead to significant declines in fish populations, affecting biodiversity and fisheries-dependent communities (Islam *et al.,* 2020). Physical and environmental factors shape aquatic ecosystems, and conservation measures are necessary to ensure species can adapt to changing conditions while maintaining ecological balance (Isroni *et al.,* 2023). Mangroves also provide essential ecosystem services that support coastal communities, including shoreline protection, carbon sequestration, and water filtration (Basyuni *et al.,* 2022). The structural complexity of mangrove forests, characterized by supporting roots and pneumatophores, enhances habitat availability and fosters high biodiversity (Nordhaus *et al.,* 2019). Accurate species identification is essential to effectively monitor and conserve fish populations in mangrove ecosystems. Although useful, traditional morphological identification methods often fail to distinguish closely related species, especially in their larval stages. This limitation has led to the increasing use of molecular approaches, such as deoxyribonucleic acid (DNA) barcoding, which provides precise genetic markers for species identification (Afrand *et al.,* 2024). DNA barcoding, particularly using mitochondrial genes such as 16 small subunit ribosomal ribosomal ribonucleic acid (16S rRNA) and cytochrome c oxidase subunit I (COI), has proven effective in identifying fish and shellfish species in mangrove habitats across Indonesia, India, and Bangladesh (Hairani *et al.,* 2023; Habib *et al.,* 2021; Ram *et al.,* 2021). This technique has revealed high genetic diversity within fish and shrimp populations and has been instrumental in resolving taxonomic ambiguities, such as the misidentification of mud crab species in the Sundarbans (Habib *et al.,* 2021). Recent studies have demonstrated the advantages of integrating morphological and molecular techniques for biodiversity assessment in mangrove ecosystems. In the Merbok Estuary, Malaysia, DNA barcoding identified 140 molecular operational taxonomic units (MOTUs), including potential cryptic species, providing a comprehensive fish inventory for the region (Abidin *et al.,* 2022). In Gorontalo, Indonesia, a combination of morphological and molecular methods identified two species of mudskippers (*Periophthalmus argentilineatus* and *P. malaccensis*) in coastal mangrove habitats (Baderan *et al.,* 2023). These findings highlight the importance of integrating multiple identification methods to improve species resolution and enhance biodiversity assessments. The east coast of North Sumatra and Aceh is known for its high fish biodiversity, including commercially and ecologically important species. However, this region faces significant threats from overfishing, habitat degradation, and pollution. Monitoring fish species abundance and composition is crucial for assessing the effect of these threats and developing effective conservation strategies. Combining these approaches can increase the accuracy of species identification by documenting fish distribution patterns and creating a database for future conservation and management initiatives. This study integrated morphological identification with 16S rRNA DNA barcoding to assess fish diversity in mangrove ecosystems along the east coast of North Sumatra and Aceh, Indonesia in 2022.

MATERIALS AND METHODS

Study site and qualification of habitat

The research was conducted for 3 months, from July to September 2022 at five locations, namely, Percut Sei Tuan, Belawan, Lubuk Kertang, Pulau Sembilan, and Langsa. Fish sampling was conducted between July and September 2022 to minimize seasonal variations in species composition. Future studies should incorporate multiseason sampling to assess temporal shifts in biodiversity. The five

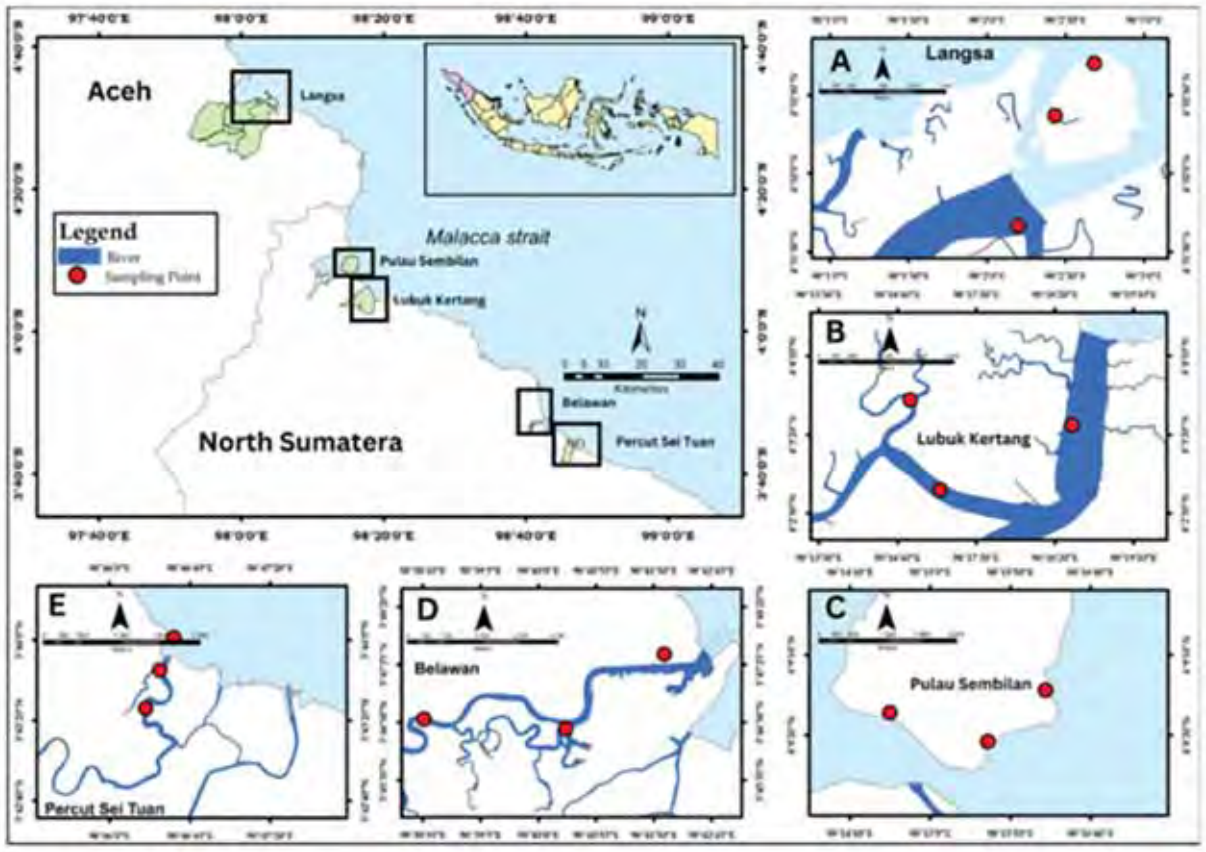


Fig. 1: Geographical location of the study area along with sampling points at Langsa (A) (Aceh Province), Lubuk Kertang (B), Pulau Sembilan (C), Belawan (D), and Percut Sei Tuan (E) of North Sumatra Province, Indonesia

locations can be found on the Eastern coast of North Sumatra and Aceh. The mangroves on Percut Sei Tuan beach are damaged by the conversion of abandoned ponds, those on Belawan beach are damaged by oil palm conversion and ponds, those in Lubuk Kertang are the result of rehabilitation, those on Pulau Sembilan are damaged by oil palm conversion and then restored, and those in Langsa are intact and continuously planted. The research stations were selected based on the characteristics of each location. Each location was studied at three stations, each with three substations. Percut, Belawan, and Langsa consist of downstream rivers, estuaries, and the sea. Lubuk Kertang is represented by estuaries and the sea (Fig. 1). Sampling effort varied slightly across these locations due to logistical constraints, though an equal number of sampling stations were selected per site. Future studies should ensure uniform sampling efforts to minimize potential biases in species richness estimates.

Sampling, preservation, and identification of fishes

Sampling was conducted using the following fishing gears owned and operated by the local fishermen: gill nets (mesh size 1, 1.5, and 3 in) and drag trawls (graduated mesh size 1,1/2 and 1/4 in). Seventy fish specimens were collected.

Fresh fish samples were collected, separated according to type, photographed one by one, and given a paper label as a temporary identity. The samples were preserved using 10% formalin, transferred to the laboratory, and observed for identification using fish identification books (Wahyudewantoro, 2018; Ahn *et al*., 2020). After identification, the samples were placed into a container with absolute ethanol.

Characteristics of mangrove forests

At each sampling location, three plots of 10 m x 10 m were set to collect fundamental forest stand characteristics. All trees within the plots were identified (Hidayat et al., 2017). The data were

subsequently utilized to compute tree density as individuals per hectare (ha).

DNA extraction and amplification and phylogenetic tree

Total genomic DNA was extracted from fish tissue muscle (fillet) using Miniprep System kit (Promega) following the manufacturer's protocol. The presence and quality of the extracted DNA template were checked through electrophoresis on 1% agarose gel, and the quantity was assessed using a nanodrop spectrophotometer (Thermo Scientific) at an absorbance ratio of 260/280 (Basyuni *et al.,* 2024). The extracted genomic DNA was amplifies using a polymerase chain reaction (PCR) machine (Sensoquest thermal cycler) and a pair of 16s rRNA primers (16s rRNA forward (F):5'-CCTGTTTANCAAAAACAT-3' and reverse (F):5'-AGATAGAAACCAACCTGG-3') (Hairani *et al.,* 2023). Subsequent to gel electrophoresis detection, all the amplification products (PCR products) were sent to Macrogen Inc. (Seoul, Republic of Korea) for further sequencing. GenBank was utilized to perform Basic Local Alignment Search Tool (BLAST) searches for the sequences obtained from the bidirectional sequencing of the fragments. Upon identifying substantial disparities between the sequences and original species, clarifications were pursued and validated through expert consultation until the BLAST results for the sequences and original species aligned in terms of genus or family (Basyuni *et al*., 2024). UGENE version 40.1 software (Salinas *et al.,* 2024) was utilized for splicing and proofreading the sequences. Phylogenetic trees were constructed with molecular evolutionary genetics analysis (MEGA X) software (Kumar *et al.,* 2018) from the 16s rRNA barcodes based on bootstrap analysis performed with 100 permutations.

Data analysis

Local distribution

The neighbor-joining (NJ) method was utilized, and the Kimura two-parameter model served as the foundation for the analysis (Laojun *et al.,* 2023 Phylogenetic trees were constructed using the distinct sequence of barcodes for each specimen and drawn by the interactive tree of life (iTOL) v. 6.7 using Eq. 1 (Letunic and Bork, 2024; Nur *et al.,* 2021):

$$D = \text{Ni.loc/N.loc x } 100\% \quad (1)$$

where *D* is the local distribution, and N.loc is the total sampling location where fishes were found.

For the study of structural diversity, the Shannon–Wiener diversity index (H') was calculated using Eq. 2 (Herrera *et al.,* 2023)

$$H' = -\sum_{i=1}^{s} Pi \ln Pi \quad (2)$$

where Pi is ni/N. The value of H' can be 0–1 (indicating low/minimal species diversity), 1–3 (indicating medium species diversity), and 3 or more (indicating high species diversity). According to the Shannon–Wiener index, the higher the diversity index, the better the ecosystem.

For the study of evenness, the evenness index (E) was computed using Eq. 3 (Setiyaningrum and Puspitasari, 2022):

$$E = \frac{H'}{H\,max} \quad (3)$$

where Ln is the experience logarithms, H' is the Shannon–Wiener diversity index, and E is the number of kinds. Using the following criteria, the population's evenness index falls between 0 and 1: High evenness is denoted by $E > 0.6$, medium evenness by $0.4 < E < 0.6$, and poor evenness by $E < 0.4$.

Statistical analysis was carried out using Analysis of variance (ANOVA) and Kruskal–Wallis tests to determine statistically significant differences in fish diversity (Pagano *et al.,* 2022) Null Hypothesis: Fish diversity is not significantly different among the sampled locations. Alternative Hypothesis: Fish diversity significantly differs among the sampled locations.

RESULTS AND DISCUSSION

Characteristics of mangrove ecosystems

Rhizophora apiculata and *Nypa fructicans* are two mangrove species consistently found across all the observation sites. Among the surveyed locations, Pulau Sembilan in North Sumatra Province hosts the highest species diversity, with 14 recorded species, followed by Lubuk Kertang with 10, Belawan and Langsa with 8, and Percut Sei Tuan with 6. The widespread presence of *Rhizophora* species in each site can be attributed to the high salinity tolerance, adaptability, and rapid growth of *R. apiculata*, making it one of the most resilient mangrove species in dynamic coastal environments (Yun *et al.,* 2022; Samal

et al., 2023). Meanwhile, *N. fructicans,* commonly known as the nipa palm, thrives in brackish water forests and along riverbanks near estuaries. Despite its ecological role, *N. fructicans* is considered an invasive species, necessitating careful management to prevent uncontrolled expansion that could alter mangrove ecosystem dynamics (Eddy and Basyuni, 2020; Widodo *et al.,* 2020).

Diversity index (H')

According to the Shannon–Wiener diversity index, the growth rates of seedlings, saplings, and mangrove trees in Pulau Sembilan and Belawan Villages and the tree level in Percut Sei Tuan fall within the medium diversity category, with H' ranging from 1.02 to 1.6 (Fig. 2). By contrast, the seedling, sapling, and tree levels in Langsa City; the seedling and sapling levels in Percut Sei Tuan; and the tree level in Lubuk Kertang Village and Langsa City are categorized as low diversity, with H' ranging from 0.21 to 0.95. Comparative studies on mangrove diversity in different regions reveal variations in their Shannon–Wiener diversity indexes (H'). For instance, in the Angke Kapuk Mangrove Protected Forest, Jakarta, the H' was 1.88 for saplings and 1.18 for seedlings, placing them in the low to moderate diversity category. The predominance of certain species, such as *R. stylosa*, across all growth stages may have contributed to the low diversity observed in this region (Basyuni *et al.,* 2018; Rumondang *et al.,* 2021 By contrast, the Tanakeke Mangrove Forest in South Sulawesi exhibited higher diversity, with 11 species from 8 families. The Shannon–Wiener diversity index was 2.01 for trees, 1.88 for saplings, and 1.18 for seedlings, suggesting a more stable and healthy ecosystem compared with that in the other locations (Setiawan and Mursidin, 2018). These findings highlight the variability of mangrove diversity across different regions and emphasize the importance of assessing local ecological conditions to inform conservation strategies.

Eveness index (E)

The evenness index (E) at different growth levels across the five study sites falls within the medium category, ranging from 0.33 to 0.97, except for the sapling level in Langsa City, which is categorized as high with an E of 1.18. In general, E values between 0.33 and 0.97 indicate that individuals of different species are fairly evenly distributed, suggesting no single species dominates the ecosystem. However, the exceptionally high E at the sapling level in Langsa City exceeds the theoretical maximum. According to Gregorius and Gillet (2022), values close to 1 indicate high evenness, and values exceeding 1 are unusual and may result from calculation or data interpretation errors. A study conducted by Sholiqin *et al.* (2021) on the south coast of Pacitan, East Java, Indonesia identified eight dominant mangrove species, with *R. stylosa* being the most abundant. The Shannon–Wiener diversity index classified the mangrove diversity in this region as low to medium. Furthermore, the evenness index (E) varied significantly between the study sites. The Teleng

Table 1: Number of individuals/ha found at the study location

No.	Species	Lubuk Kertang	Pulau 9	Belawan	Percut Sei Tuan	Langsa
1.	*Avicennia alba*		87	427	473	
2.	*A. marina*	147	240	367	713	
3.	*A. officinalis*	213	240	560		373
4.	*Bruguiera gymnorrhiza*	533	7	427		47
5.	*B. sexangula*		240			
6.	*B. cylindrica*				20	
7.	*Excoecaria agallocha*			93	7	
8.	*Ceriops tagal*	267	1.247			67
9.	*Lumnitzera racemosa*		47			
10.	*N. fructicans*	380	187	73	35	7
11.	*R. apiculata*	2.507	1.007	220	227	2.147
12.	*R. mucronata*	53	60			13
13.	*R. Stylosa*		1.387			13
14.	*Scyphiphora hydrophylacea*	240	7			
15.	*Sonneratia alba*	47	487			
16.	*Xylocarpus granatum*	73	147	40		173
	Total	4.460	5.387	2.207	1.673	2.840

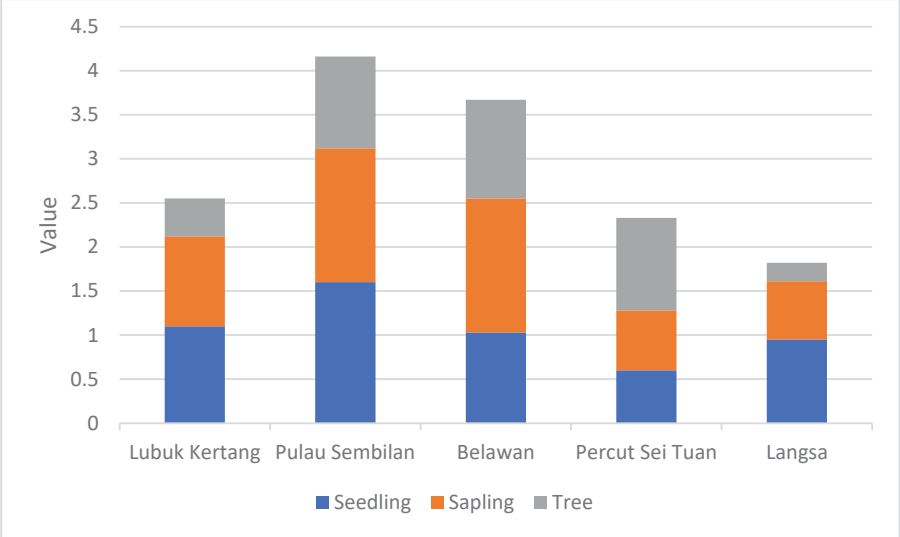


Fig. 2: Diversity index values for mangrove plants at the observation location

Ria Estuary exhibited a higher evenness index than the other locations, which is suggestive of its more balanced species distribution and relatively stable ecosystem.

Index richness (R)

The Margalef species richness index (R) across all observation locations fall within the low category, ranging from 0.67 to 1.63 (Fig. 3). This finding suggests that these mangrove ecosystems have relatively low species richness, indicating limited species diversity. Species richness in mangrove ecosystems is influenced by various ecological and environmental factors, including salinity, tidal fluctuations, substrate composition, and anthropogenic pressures, such as deforestation and pollution (Nagelkerken *et al.,* 2018). The relatively low R values observed in this study suggest that the mangrove ecosystems in the surveyed areas may be experiencing environmental stressors that limit their species diversity. Comparative studies reported varying species richness levels in different mangrove regions. For example, a study in the Segara Anakan Lagoon, Indonesia, found an R value ranging from 2.01 to 3.50, indicating moderate to high species richness due to the presence of diverse mangrove habitats (Jennerjahn *et al.,* 2024). Similarly, mangrove forests in Malaysia's Matang Mangrove Reserve reported R values above 2.5, suggesting a diverse and well-preserved ecosystem (Goessens *et al.,* 2014). The low species richness observed in this study could be attributed to habitat fragmentation, pollution, and mangrove resource overexploitation, all of which have been identified as key threats to mangrove biodiversity in Indonesia (Basyuni *et al.,* 2021; Sari *et al.,* 2022). In addition, the species dominance by a few genera, such as *Rhizophora* and *Avicennia*, may reduce overall species richness by limiting the establishment of other mangrove species (Alongi, 2018).

Distribution and species composition

Sixty-two fish species, representing 38 families, were identified based on morphological characteristics. The most abundant families are Serranidae, Pomacentridae, and Labridae, which are commonly found in mangrove and reef-associated ecosystems. DNA barcoding successfully identified 17 out of the 50 morphologically identified species; the remaining nine species required further molecular analysis for confirmation. Morphological analysis also revealed high genetic diversity within several species, suggesting the presence of multiple subpopulations. However, the overall species diversity and abundance exhibit a decline over the 2-year monitoring period, raising concerns about the long-term stability of fish populations in these ecosystems. These findings highlight the significant discrepancies between morphological and molecular identification,

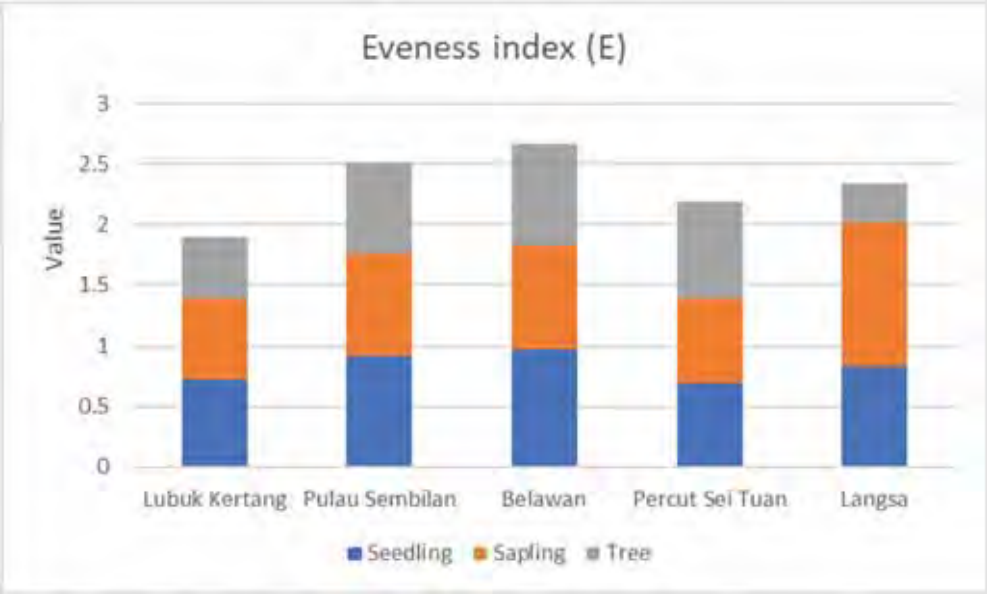


Fig. 3: Evenness index for mangrove plants at the observation location

emphasizing the need for expanded genetic reference databases. The dominance of species X and Y across multiple sites suggests their adaptability to mangrove ecosystems, and the restricted distribution of species Z may indicate specific habitat preferences or localized threats. These patterns underscore the importance of site-specific conservation strategies. For the ANOVA test results: F-statistic = 543.89, p-value = 4.29 × 10^{-20} (highly significant). For the Kruskal–Wallis test results: H-statistic = 23.08, p-value = 0.00012 (highly significant) (Table 2). Given that both tests yielded extremely low p-values ($p < 0.05$), the null hypothesis is rejected, that is, fish diversity significantly differs across the five locations (Percut Sei Tuan, Belawan, Lubuk Kertang, Pulau Sembilan, and Langsa).

Identification of fish species

Table 2 shows the results of fish field identification in the study sites and confirmation using 16s rRNA barcodes based on BLAST search (identity and query cover). The 16S rRNA barcode sequences reported in this paper has been deposited in the GenBank/ he European Nucleotide Archive (ENA) and the DNA Data Bank of Japan (DDBJ).

Biodiversity assessment is a key aspect of biological conservation. However, current biodiversity assessment methods generally need improvements because they are crucial in the future of biodiversity, forest resources, and aquatic ecosystems. Biodiversity in mangrove ecosystems is affected by river runoff that transports large amounts of nutrients and organic matter (Pasquaud *et al.,* 2015). Fish diversity in mangrove ecosystems is influenced by various ecological and environmental factors, including habitat structure, water quality, and anthropogenic activities, such as overfishing and habitat destruction (Nagelkerken *et al.,* 2018). The dominance of Serranidae, Pomacentridae, and Labridae aligns with a previous study indicating their ability to adapt to mangrove and coral reef environments and their role as key components of coastal food webs (Asriyana *et al.,* 2020). Among the 17 fish species, 10 were confirmed using 16S rRNA with 100% identity and 100% query (Table 3). The sequences from these 14 fish species perfectly match a reference sequence in the database with 100% identity, without mismatches or gaps in the aligned region. This finding suggests that the 16S rRNA gene is highly conserved for these species in the reference database. Two species, *Larimichthys crocea* and *Thunnus maccoyii*i, were found to be critically endangered and endangered, respectively (Table 3), revealing the ability of this technique to facilitate the identification of at-risk species and the formulation of successful conservation plans. The combination of morphological and molecular techniques provides a comprehensive assessment of fish biodiversity.

Table 2: ANOVA and Kruskal–Wallis test

Statistical test	Test statistic	P-value	Interpretation
ANOVA	543.89	4.29×10^{-20}	Significant differences exist
Kruskal-Wallis	23.08	0.00012	Significant differences exist

Table 3: Field identification of fish species samples with 16s rRNA barcode data and BLAST search results

ID	Field identification species	Accession	Length	Identity (%)	Query cover (%)	1st Hit	1st Hit Accession	Locality
B1	*Larimichthys crocea*	PV174210	458	100	100	*Larimichthys crocea*	MF004337	Belawan
B18	*Larimichthys crocea*	PV174211	645	100	100	*Larimichthys crocea*	AP006002	Belawan
BLW4_16	*Epinephelus fuscoguttatus*	PV174212	366	100	95.63	*Epinephelus hexagonatus*	HQ840453	Belawan
BLW8_16	*Larimichthys crocea*	PV174213	511	100	99.41	*Larimichthys crocea*	AP006002	Belawan
BLW18_16	*Elops saurus*	PV174215	491	97.36	97.56	*Elops saurus*	NC_005803	Belawan
L30	*Seriola lalandi*	PV174217	490	100	100	*Seriola lalandi*	KX234657	Langsa
LGS6_16	*Sphyraena jello*	PV174219	651	90.02	88.63	*Sphyraena barracuda*	NC_022484	Langsa
GS7	*Larimichthys crocea*	PV174220	560	100	100	*Larimichthys crocea*	GU120089	Langsa
LGS8	*Thunnus maccoyii*	PV174221	350	100	100	*Thunnus maccoyii*	LN558761	Langsa
LK3_16	*Scomberoides commersonnianus*	PV174223	490	99.59	99.59	*Scomberoides commersonnianus*	MN023229	Lubuk Kertang
LK25_16	*Elops hawaiensis*	PV174225	607	99.51	99.51	*Elops hawaiensis*	NC_005798	Lubuk Kertang
P24	*Sillago attenuate*	PV174228	630	100	100	*Sillago attenuata*	MF572044	Pulau Sembilan
PC12	*Cottoperca gobio*	PV174230	560	100	100	*Cottoperca gobio*	AY520102	Percut Sei Tuan
PCT1_16	*Epinephelus coioides*	PV174231	618	94.04	89.32	*Epinephelus coioides*	NC_011111	Percut Sei Tuan
PCT4	*Hexanematichthys sagor*	PV174232	560	94.15	91.96	*Hexanematichthys sagor*	FJ626072	Percut Sei Tuan
PS17_16	*Ilisha elongata*	PV174234	630	99.51	96.19	*Pellona ditchela*	AP011609	Pulau Sembilan
PS28	*Larimichthys crocea*	PV174236	420	100	100	*Larimichthys crocea*	GU120089	Pulau Sembilan

The present work used 16S rRNA barcoding, a well-conserved genetic marker effective for broad taxonomic classification. However, this method has limitations in distinguishing closely related species due to low genetic variability. By contrast, the COI gene is commonly used for species-level identification because it provides greater resolution. Emerging techniques such as environmental DNA metabarcoding offer noninvasive biodiversity monitoring by detecting fish DNA in water samples. Although 16S rRNA barcoding validated 17 species in the current research, some species require additional molecular markers for precise identification. Morphological identification remains an essential tool for field surveys; however, it has limitations in distinguishing cryptic species and early life stages. DNA barcoding using mitochondrial genes, such as 16S rRNA and COI, has proven effective in improving species identification accuracy (Baderan *et al.*, 2023). The present work used 16S rRNA due to its efficiency in resolving phylogenetic relationships among closely related fish species. However, COI and internal



Fig. 4: Richness index of mangrove flora at observation location

transcribed spacer markers are known to provide high taxonomic resolution in some cases (Imtiaz *et al.,* 2017). Future studies should incorporate multiple markers to enhance species-level identification and confirm ambiguous classifications. The discovery of high genetic diversity within several species suggests the presence of localized adaptations and subpopulations, which could have important implications for fisheries management and conservation (Hubert *et al.,* 2015). Although DNA barcoding is already widely used tool, the current study contributed to its further development by applying it to the poorly studied mangrove fish communities along the east coast of Sumatra and Aceh. The integration of morphological and molecular approaches enables an accurate assessment of biodiversity, particularly for cryptic species. Future research should focus on expanding local genetic reference databases to improve taxonomic resolution and enhance conservation efforts.

In this study, 88% of fishes distributed on the eastern coast were identified in the field work (Fig. 5). Molecular work successfully confirmed 17 out of the 50 sequencing data (58%). The most abundant families are Serranidae, Pomacentridae, and Labridae. Morphology analysis also detected the presence of some rare and endangered species, including the humphead wrasse (*Cheilinus undulatus*) and giant grouper (*Epinephelus lanceolatus*). The overall species diversity and abundance have exhibited a decline over the 2-year monitoring period. This finding corresponds with previous research highlighting the benefits and drawbacks of both methodologies. Conventional field identification, although beneficial for swift evaluation, may be affected by observer bias and contextual factors (Barreto *et al.,* 2022). Although DNA barcoding and environmental deoxyribonucleic acid (eDNA) metabarcoding have demonstrated enhanced accuracy, they are frequently constrained by insufficient reference datasets (Keck *et al.,* 2022). The integration of both methodologies improves species detection, particularly for cryptic and immature species that are challenging to identify morphologically (Sheth and Thaker, 2017). Only 17 out of the 62 morphologically identified species were confirmed using 16S rRNA barcoding. This discrepancy may be attributed to the gaps in reference databases, PCR amplification failures, or cryptic species misclassified in morphological assessments (Phukuntsi *et al.,* 2016). Future studies should expand genetic reference libraries and incorporate multiple genetic markers to improve species validation.

This study demonstrates the efficacy of DNA monitoring for assessing fish biodiversity and

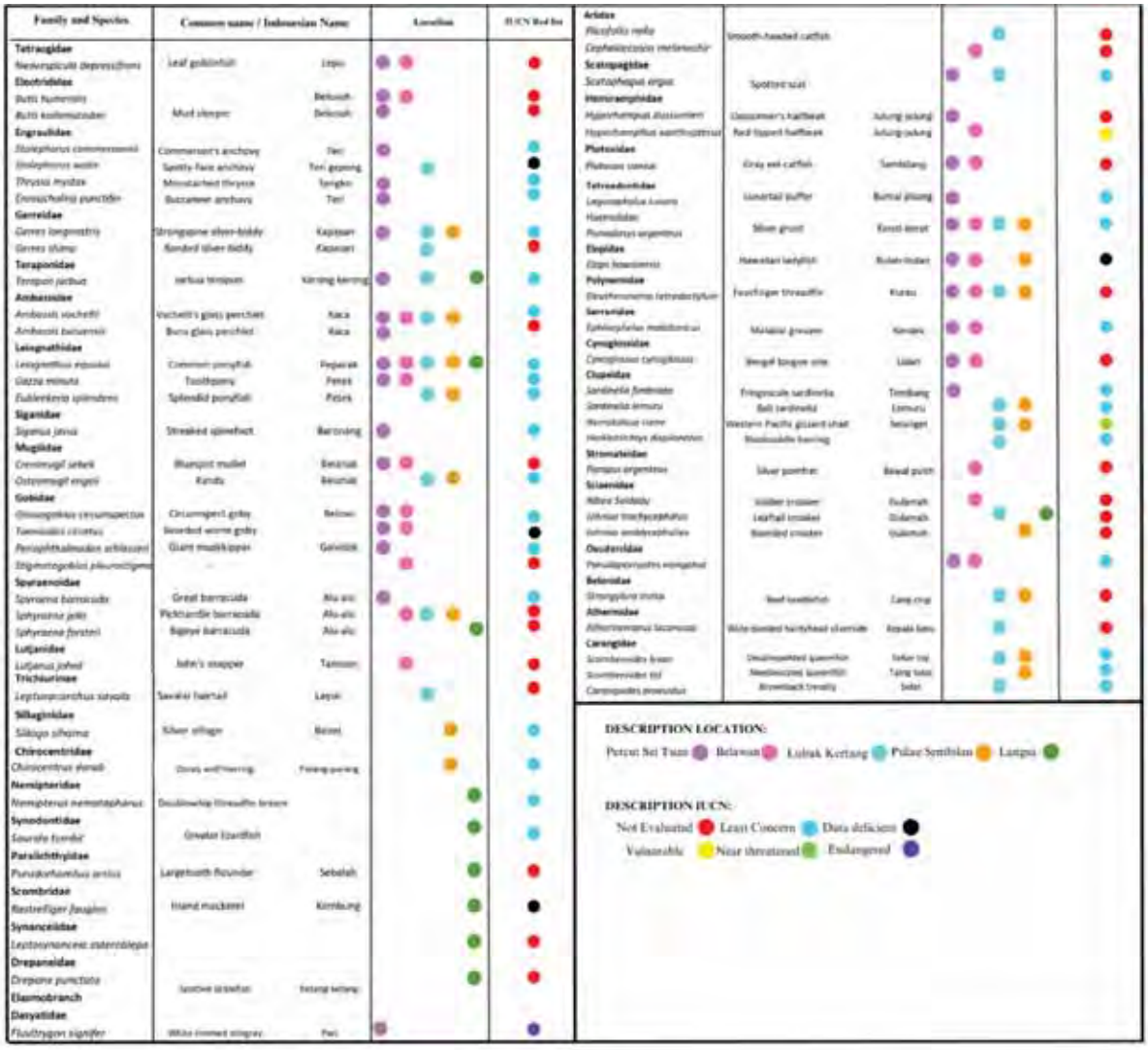


Fig. 5: Identification of family, species fish diversity, and International Union for Conservation of Nature (IUCN) status through field work on the study sites

abundance in the east coast of North Sumatra and Aceh, Indonesia (Fig. 6). The decline in species diversity and abundance over the 2-year monitoring period highlights the urgent need for conservation efforts in the region. In addition, the detection of rare and endangered species using DNA monitoring underscores the importance of protecting these species and their habitats. DNA monitoring can provide significant results.

The results of this study demonstrate the efficacy of DNA monitoring for assessing fish biodiversity and abundance in the east coast of North Sumatra and Aceh, Indonesia (Fig. 7). The Shannon–Wiener Index (H') value shows significant differences among the locations, indicating that the diversity of fish from each location vary and is strongly influenced by environmental factors. Meanwhile, the evenness index (E) tends to be high at each location, indicating that fishes are generally uniformly distributed within each location. Confidence interval (CI) values were added to ensure that the values are accurate and confirm the variation in fish species diversity among the sites. DNA monitoring can also provide significant results. The dominance of Serranidae (groupers),

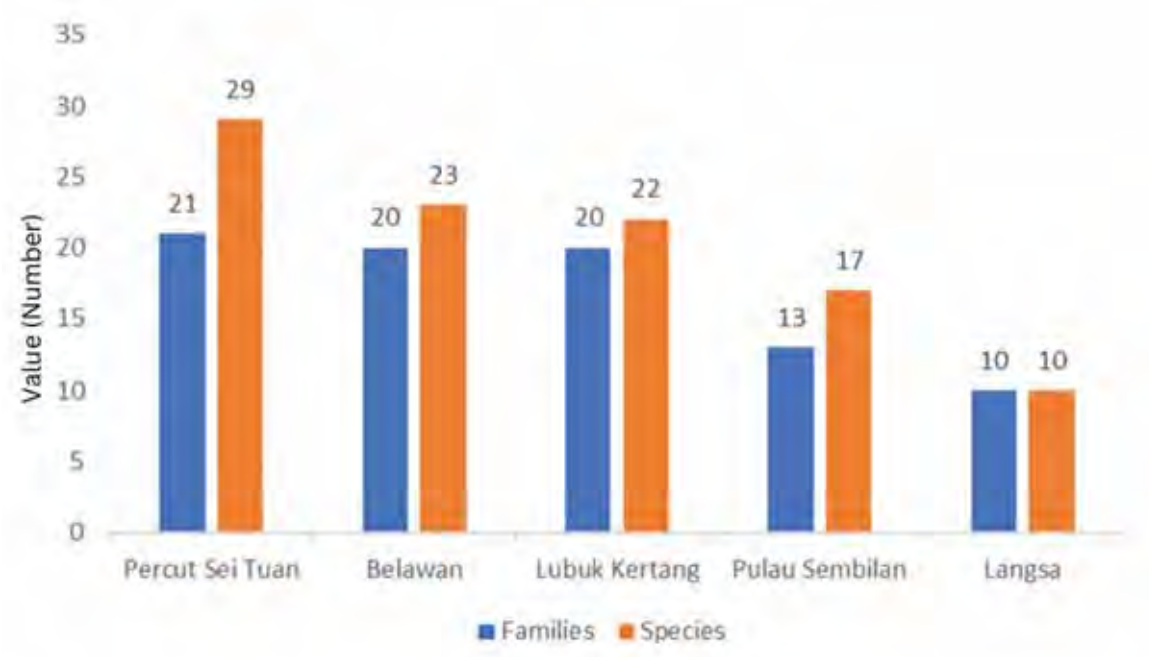


Fig. 6: Distribution of fish in the east coast of North Sumatera and Aceh, Indonesia

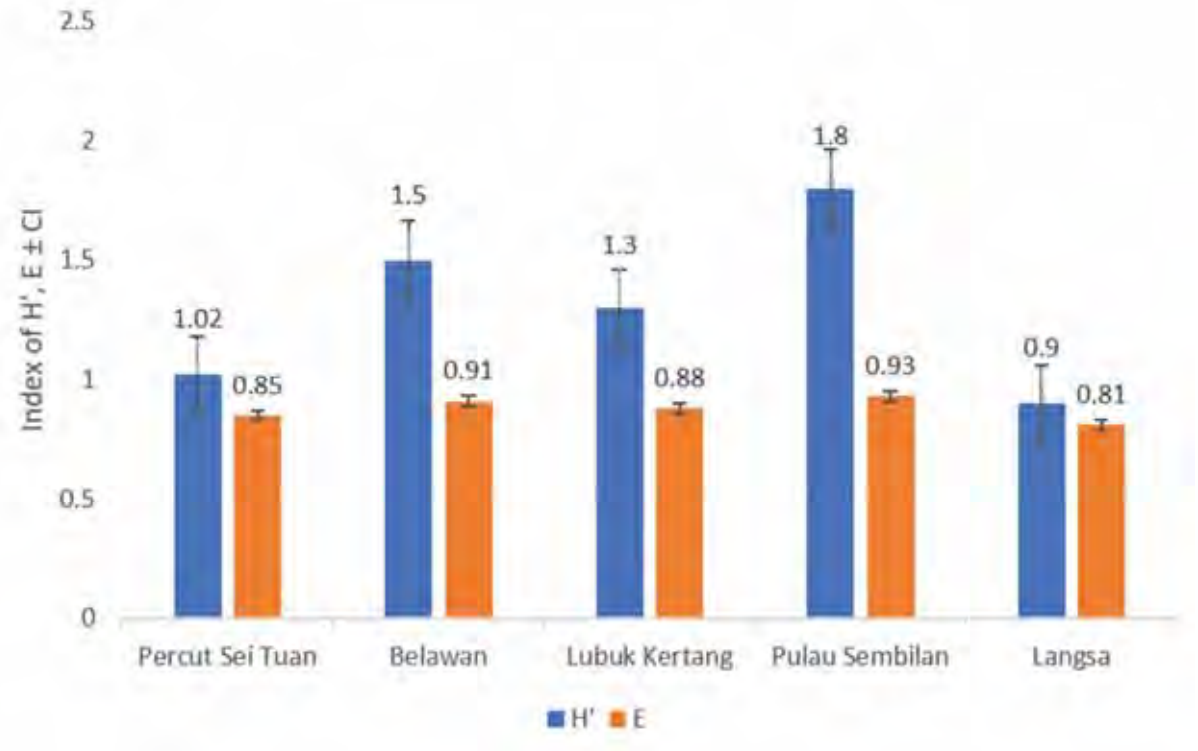


Fig. 7: Indices of diversity and evenness of fish in the research sites

Pomacentridae (damselfish), and Labridae (wrasses) is consistent with previous studies in tropical reef and coastal habitats (Du *et al.,* 2020). These families play significant ecological roles: Serranidae includes top predators that regulate fish populations, Pomacentridae are key reef inhabitants influencing coral health, and Labridae contribute to reef maintenance by controlling algal growth (Seemann *et al.,* 2018). The presence of these families suggests that the area supports a functional mangrove ecosystem. In general, the fish diversity in the mangrove ecosystems of North Sumatra and Aceh is influenced by various environmental factors such as water salinity, which in turn is affected by tides and rainfall. Optimal salinity allows various fish species to grow and reproduce, and extreme salinity fluctuations can limit species distribution. Salinity levels differ at each location where mangroves grow in North Sumatra and Aceh (Basyuni *et al.,* 2019), causing variations in the composition of mangrove species that grow. The density of vegetation determines the composition of fish that provide ideal habitat for protection, spawning, and food sources. In addition, the distribution of fish diversity varies because each species exhibits a specific type of salinity tolerance per habitat (Hairani *et al.,* 2023).

A heatmap representation showing the distribution of fish species and families across the five different study sites. Purple color indicates the presence of a species or family at a site, with darker color intensity indicating higher abundance (Fig. 8). Some species are found to be widespread in several locations, while others only occur in certain locations. In total, 62 species were identified exclusively using morphology, and 17 species were identified exclusively through DNA barcoding. This study represents the fish species detected across five different sampling locations: Percut Sei Tuan (28 species), Belawan (23 species), Lubuk Kertang (23 species), Langsa (10 species), and Pulau Sembilan (17 species). The total number of species per site using DNA Barcoding was 3 for Percut Sei Tuan, 5 for Belawan, 2 for Lubuk Kertang, 4 for Langsa, and 3 for Pulau Sembilan. In this study, 62 fish species belonging to 39 families were identified using morphological characteristics. DNA barcoding successfully confirmed 17 species, with some



Fig. 8: Heatmap analysis of species and family distribution patterns from each site, Langsa (LGS), Lubuk Kertang (LK), Pulau Sembilan (PS), Belawan (BEL), and Percut Sei Tuan (PST)

requiring further genetic analysis for precise identification. Identification using the combination of morphology and DNA barcoding revealed 62 fish species identified morphologically and 17 fish species successfully validated using DNA barcoding. Molecular analysis of the phylogenetic tree revealed genetically distinct lineages. According to their IUCN status, two fish species were found to be threatened with extinction, namely, *L. crocea* and *T. maccoyii* categorized as endangered and critically endangered, respectively. This result shows the potential of the mangrove ecosystem as a good protection habitat for these vulnerable species. Other species such as *Elops* sp. that appear in some locations indicate the possibility of the hidden diversity of these fishes, which require further exploration. This finding is consistent with the previous study of (Hubert *et al.* 2015), which highlighted the ability of DNA barcoding to uncover cryptic diversity and differentiate morphologically similar species. The differences in species composition between suggest variations in species detectability (Fig. 8), possibly due to seasonal fluctuations, habitat degradation, or fishing pressure (Winn *et al.,* 2021). Traditional morphological identification has long been used in fish biodiversity assessments; however, it faces several limitations. Phenotypic plasticity, cryptic species, and ontogenetic variations can lead to misidentification, particularly in species with overlapping morphological traits. Molecular techniques, such as 16S rRNA and COI barcoding, provide an accurate and reproducible approach by relying on genetic markers that remain stable across different life stages and environmental conditions. Moreover, DNA-based methods enable the detection of cryptic diversity and rare species that may be overlooked in conventional surveys. DNA barcoding and phylogenetic studies allow for accurate species identification, especially cryptic species that are difficult to distinguish morphologically. These methods also help us understand the genetic diversity within mangrove populations, which is important in determining the level of adaptation to environmental changes and external threats, such as climate change and pollution (Gostel and Kress, 2022). Nevertheless, morphological analysis remains necessary to understand the structure and growth of mangrove plants in relation to environmental factors, such as salinity, substrate, and tides. The combination of these two methods provides a comprehensive picture of the condition of mangrove ecosystems and supports science-based decision-making in conservation. In long-term conservation planning, the integration of molecular and morphological methods is helpful in monitoring the health of ecosystems and the effectiveness of mangrove rehabilitation. Knowing the genetic variation between populations allows the development of restoration strategies that consider species' resilience to specific environmental stresses. In addition, genetic mapping can help in determining priority conservation zones to protect mangrove populations with high genetic diversity, which make them resilient to climate change and anthropogenic pressures. Studies on fish diversity in other ecosystems also showed that mangrove ecosystems can be potential habitats for various fish species. Henc, species richness varies from one location to another, indicating that the environmental factors in each location are influential. The Shannon–Wiener Index (H') in the whole research area (0.9–1.8) tends to be higher than that in the restored mangrove ecosystem in Malang, Indonesia (H'<1) (Ridlo *et al.,* 2020). The relatively low diversity of the latter indicates that restoring this mangrove forest requires a long time to rebuild the fish community and the full function of the mangrove ecosystem. Research conducted on natural mangrove conditions in Qinzhou mangrove forest, China revealed the presence of a semi-closed estuary system that allows stable environmental conditions; 67 fish species were found in this location, which is also known as a large and protected mangrove forest (Huang *et al.,* 2016). A high level of diversity was also recorded in the mangrove forests of Oman with 177 fish species; these mangrove forests are in active conservation and have a close relationship with the open ocean system (Al Jufaili *et al.,* 2021). Seasonal variations significantly affect the composition and abundance of fish species in mangrove waters. Indonesia has two seasons, so each seasonal change alters the environmental conditions, such as salinity, temperature, and water flow; fish species can grow and develop under low salinity, which is optimal in finding nursery habitats (Purwanto *et al.,* 2022). Climate change plays a role in biodiversity dynamics by affecting fish migration patterns, reproductive cycles, and food availability. Some species such as baronang (Siganidae), mullet (Mugilidae), and snapper (Lutjanidae) may use mangrove areas

seasonally as spawning and rearing grounds before migrating to offshore waters. The high species richness observed in Percut Sei Tuan and Belawan aligns with findings from fish diversity studies in coastal areas, where estuarine and mangrove-associated habitats serve as important nursery grounds (Sheaves *et al*., 2015). The low species richness in Pulau Sembilan and Langsa may be attributed to habitat fragmentation or inadequate sampling efforts (Basyuni *et al.,* 2022). The observed decline in species diversity and abundance over the 2-year monitoring period highlights the urgency of conservation efforts in the region. Previous research documented mangrove deforestation, coastal pollution, and overfishing as key drivers of fish population decline (Carlson *et al.,* 2021). To address this problem, future research should focus on longitudinal monitoring programs (Bhowmik *et al.,* 2022) and the expansion of genetic reference databases for accurate species identification. Moreover, advancements in eDNA metabarcoding and remote sensing technologies can provide noninvasive and efficient biodiversity assessments (Zhang *et al.,* 2023Expanded genetic reference databases can help improve the accuracy of species identification through DNA barcoding methods by providing a large amount of comparison data to match DNA sequences with previously identified species. With many species documented in the database, identification errors due to lack of references can be minimized (Gostel and Kress, 2022). This step is especially important for the taxonomy of species that are difficult to distinguish morphologically. In addition, an extensive database enables the detection of new or invasive species that may not have been conventionally recognized, thus contributing to accurate conservation efforts and ecosystem monitoring (Imtiaz *et al.,* 2017). In future biodiversity studies, a complete genetic database will serve as an important tool for species monitoring and protection. For example, in mangrove ecosystems and surrounding waters, widely referenced DNA barcoding methods can be used to quickly and noninvasively identify organisms without having to capture or damage them. This approach allows for an efficient and real-time monitoring of ecosystems, aiding in scientific-based conservation decision-making. Obstacles in the form of limitations related to taxonomy and databases were encountered in the present study. Several taxa of identified species showed low sequence similarity with existing GenBank references. Molecular-scale studies, such as through DNA barcoding, are warranted to validate morphological species identification. The limitation of using one molecular marker resulted in the limited resolution of mangrove ecosystem fish taxonomy. To overcome these challenges, future research can be carried out by integrating several molecular markers, such as COI with high discriminatory power for identification. In addition, technological advances with eDNA metabarcoding applications can be an opportunity for monitoring fish diversity.

Conservation implications

The observed decline in species richness and abundance over the 2-year study period underscores the pressing need for conservation measures. The detection of rare and endangered species, such as *C. undulatus* (humphead wrasse) and *E. lanceolatus* (giant grouper), further highlights the ecological significance of these mangrove ecosystems. Strengthening habitat protection, enforcing sustainable fishing practices, and promoting community-based conservation programs are essential for mitigating biodiversity loss in these coastal areas.

The phylogenetic tree constructed using 16S rRNA molecular markers represents the evolutionary relationships among the fish species identified in a mangrove ecosystem or estuarine habitat in North Sumatra and Aceh (Fig. 9). DNA barcoding successfully identified 17 out of the 62 morphologically identified species; 9 species required further investigation. The bootstrap value on the phylogenetic tree varies with different CIs of 0.63–1. Bootstrap values of more than 0.70 (70%) indicate strong support for the clade in the construction of the phylogenetic tree. The clades formed from each species and clustered indicate that the species have a high relationship and confirm the accuracy of the use of molecular markers. According to the phylogenetic tree, *L. crocea* (critically endangered) and *T. maccoyii* (endangered) are in a specific clade, indicating their unique evolutionary history different from the other species. The high genetic diversity within some species indicates subpopulation structures, which are critical for conservation planning in mangrove habitats. Some species, such as *Elops* sp. and *Pellona ditchela*, appear

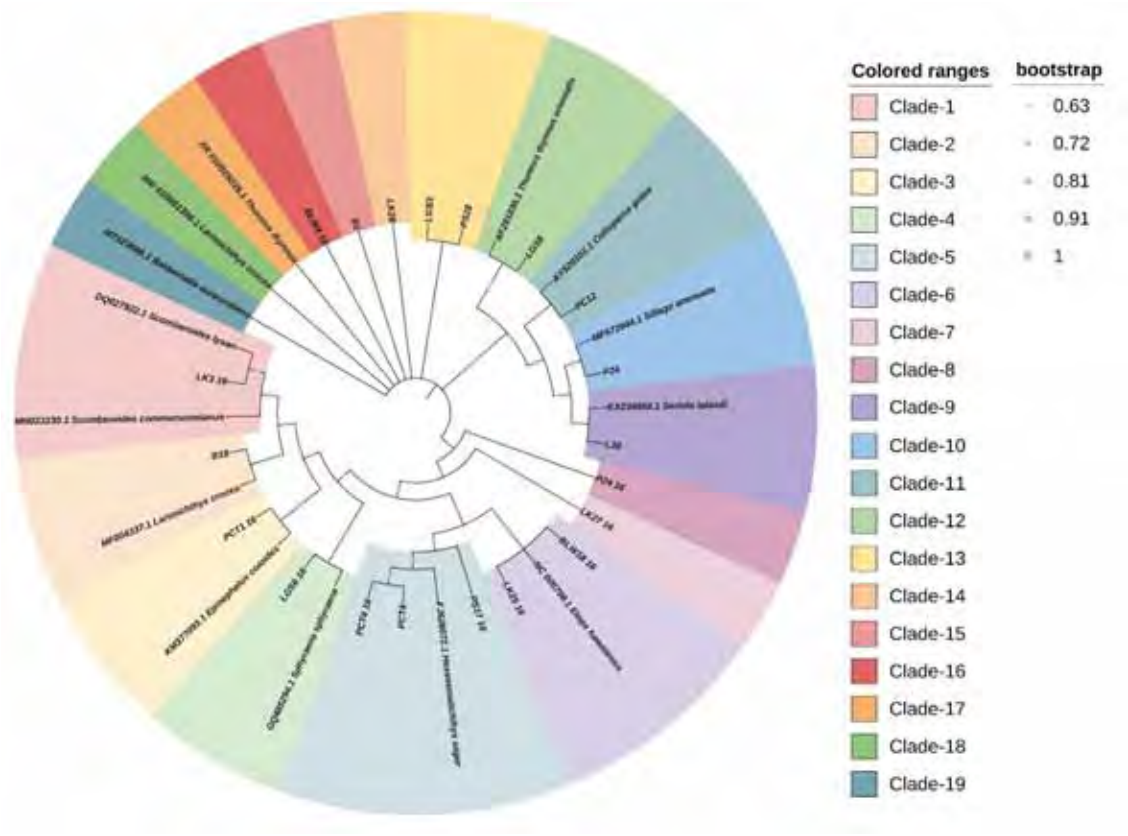


Fig. 9: Phylogenetic diversity of fishes from five sites derived from DNA barcode data

multiple times, which may indicate cryptic diversity (different species that look similar morphologically but are genetically distinct). Mangrove forests serve as nurseries and feeding grounds for many of these species, particularly juvenile fish and crustaceans. The high fish diversity in these mangrove ecosystems can be a reference for sustainable fish management. These mangrove ecosystems can be a natural nursery, hence requiring active conservation efforts. Policy recommendations include protecting estuarine mangrove habitats by limiting fishing in spawning areas, especially for endangered fish species. Conservation measures for endangered fish must be strengthened based on the results of studies at each location, such as *L. crocea* and *T. maccoyii* being threatened with extinction based on the IUCN. Furthermore, ecosystem-based fish management must be carried out by looking at the ecological considerations of each identified species. Community involvement can be invoked by integrating scientific knowledge and traditional knowledge from the community. The presence of commercially important fish (*Epinephelus fuscoguttatus*) highlights the economic value of mangrove ecosystems for local fisheries (Kadim *et al.,* 2022This phylogenetic analysis provides critical insights into fish biodiversity in mangrove ecosystems. For strengthened conservation efforts, long-term monitoring using eDNA metabarcoding is recommended to detect species shifts due to environmental changes. Restoration programs should focus on preserving key mangrove habitats that support nursery grounds and fisheries. Further genetic studies are needed for species requiring advanced taxonomic classification (Wasik and Pattison, 2024). Mangrove ecosystems support the early life stages of many fish species. Their complex roots provide a protective habitat for larvae and young fish from predators and strong currents (Hammerstein *et al.,* 2024). These structures also serve as spawning grounds for many fish species,

providing an environment rich in food resources, such as plankton, detritus, and small invertebrates, which are essential for the growth of young fish. Ecologically, mangrove ecosystems are critical to maintain the viability of fish populations and the biodiversity of coastal waters. Mangroves act as a nursery for fish that will later migrate to open waters and as a provider of organic carbon that supports the marine food chain. Therefore, the conservation and rehabilitation of mangrove forests are necessary to ensure the continuity of these ecological functions and support the natural regeneration of various fish species. Rehabilitation efforts are carried out through the Community-Based Mangrove Management (CBMM) program, which aims to restore degraded mangrove forests and protect coastal areas in an effort to conserve biodiversity (Damastuti *et al.,* 2022). In addition, the success of mangrove forest rehabilitation through restoration has significance in forest conservation efforts. This goal is in line with the government's ambition to restore 600,000 ha of mangrove forests in Indonesia in a sustainable manner (Sasmito *et al.,* 2023). The important role of community governance is to maintain and preserve the integrity of restored mangrove forests and their biodiversity. Mangrove forest restoration and conservation efforts should consider the importance of poverty alleviation through alternative livelihood options and community awareness activities related to optimal forest resource management (Rejeki *et al.,* 2021). Mangrove forest rehabilitation in Indonesia has been carried out with a comprehensive goal of recovering lost biodiversity through sustainable forest restoration strategies. One important approach is to strengthen community-based mangrove management. As key stakeholders in forest conservation, local communities mut be supported with sustainable livelihood programs, such as aquaculture and ecotourism, to reduce their dependence on exploiting forest resources (Khan *et al.,* 2020). Exploitation of fisheries resources by using trawling or netting small fish causes a decline in fish populations. The development of coastal areas, such as the power plant in Lubuk Kertang and the conversion of land into ponds, narrows the living space and hinders the growth of mangrove ecosystems. Therefore, strict conservation strategies must be applied to protect biodiversity in mangrove ecosystems without triggering conflicts with neighboring communities. One approach is sustainable fisheries management, such as the Silvofishery system that has been applied to various mangrove forest areas. This conservative measure will be an addition to restoration, so that the ecological function of mangroves can be stabilized (Pandiangan *et al.,* 2024). Other strategies include the formation of forest farmer groups and increased community participation in conservation. Mangrove rehabilitation through restoration activities with local environmental conditions is essential to restore ecological functions, such as providing habitat for fish and other organisms. In addition, the implementation of protection zones and restrictions on fishing activities in vulnerable areas will help maintain the balance of fish populations. The use of environmentally friendly fishing gear and the enforcement of no-take periods during the spawning season are also effective in ensuring the survival of fish species that depend on mangrove ecosystems. Involving local communities in conservation programs, such as mangrove-based ecotourism and environmental education activities, can increase their awareness and concern for protecting these ecosystems. Through a holistic and scientific-based approach, biodiversity in mangrove ecosystems can be protected in the long term while providing economic and ecological benefits to the surrounding communities. The health of a mangrove ecosystem can be seen in the variability of fish diversity living in the mangrove ecosystem over time. Long-term monitoring is needed to ensure the value of sustainable fish diversity. This program can be maximized by updating technology in monitoring fish diversity. The eDNA method, which identifies fish diversity using metadata from water samples collected in mangrove ecosystems, also increases taxonomic resolution. Advanced technologies, such as underwater camera monitoring and hydroacoustic surveys, can be employed to minimize disturbance. Regular monitoring can also be carried out by involving communities such as local fishermen who live around mangroves to increase data coverage and conservation efforts from the community. However, the challenges to long-term monitoring include seasonal fluctuations and difficulty in identifying morphologically similar species. In addition, ongoing funding, ecological and taxonomic expertise, and cross-disciplinary collaboration are required for implementation. Collaborative engagement is needed

for every stakeholder who plays a role in this continuous monitoring to overcome these challenges.

CONCLUSION

The findings of this study highlight significant variations in fish biodiversity across different mangrove sites. The integration of morphological and molecular approaches provided a comprehensive assessment of species diversity, revealing 62 species detected through morphological identification, 17 of which were confirmed through DNA barcoding. This discrepancy underscores the need for expanding genetic reference databases, as some species may lack adequate sequences for comparison. In addition, the differences in species composition across sites suggest that habitat quality, environmental stressors, and anthropogenic activities shape fish communities. The dominance of *Leiognathus equula*, *Ambassis vachellii*, and *Pomadasys arg*enteus across multiple locations indicates their adaptability to mangrove ecosystems. Meanwhile, the limited distribution of certain species suggests their specific habitat dependencies or localized threats. The decline in overall species diversity over the 2-year monitoring period raises concerns about habitat degradation and the effectiveness of current conservation strategies. Moreover, the detection of endangered and critically endangered species (*L. crocea* and *T. maccoyii*) underscores the urgency of targeted conservation measures. Future research should focus on several key areas to enhance conservation and biodiversity monitoring efforts. Expanding genetic reference databases is crucial to improving species identification accuracy through DNA barcoding. Long-term monitoring programs should also be established to track changes in fish biodiversity and assess ecosystem health over time. Habitat protection and restoration efforts, such as mangrove reforestation and enforcement of sustainable fishing practices, must be prioritized to mitigate habitat loss. Community engagement is also vital in strengthening biodiversity conservation. Increasing local participation through education programs and citizen science initiatives can foster awareness and encourage responsible resource management. The integration of advanced technologies, including eDNA metabarcoding and remote sensing, offers efficient and noninvasive methods for biodiversity assessment, allowing for a comprehensive and real-time monitoring of fish populations. With these strategies, biodiversity conservation in mangrove ecosystems can be strengthened to ensure the sustainability of fisheries and the resilience of coastal ecosystems in the face of environmental challenges. The limitations of this study are as follows: closely related species may still have identical 16S rRNA sequences, leading to possible taxonomic uncertainty at the species level. Some species may have identical or highly similar sequences, leading to taxonomic uncertainty. Future studies should incorporate COI or whole-genome sequencing (WGS) to refine species identification. The reference database lacks certain fish species or has incomplete records, and the remaining 13 fish specimens may have low identity matches or ambiguous identifications. A collaborative approach involving researchers, policymakers, local communities, and conservation organizations is essential for ensuring the long-term sustainability of fisheries and the protection of coastal biodiversity. Forest rehabilitation through restoration aims to repair the diversity of mangrove ecosystems. The involvement of external organization and communities is crucial to the success of national and regional mangrove rehabilitation projects. In addition to the legal safeguards and sanctions in place for fishing practices that damage the ecosystem, government policies concerning mangrove rehabilitation must include ways to communicate and educate the public on the importance of managing natural resources and protecting forests. Continued research and monitoring efforts will be key to understanding the dynamics of fish populations and addressing the ongoing challenges posed by environmental changes and human activities. Another limitation of this study is the exclusive use of 16S rRNA barcoding, which may not differentiate closely related species.

AUTHOR CONTRIBUTIONS

M. Basyuni, the corresponding author, contributed to this conceptualizing this study, applying for funding, prepared the manuscript text. Irmawati contributed to this collected data and analysis data. A. Mubaraq contributed to acquisition of data and writing manuscript. A. Susilowati helped to writing manuscript and input data. A.B. Rangkuti contributed writing the manuscript and revised manuscript. Desrita contributed to writing manuscript and reviewing the manuscript. A.A. Aznawi analyzing data

and writing manuscript. S.S. Mustaniroh contributed to data analysis and reviewing the manuscript. S.H. Larekeng statistical and writing the initial manucript. A.H. Salman contributed to spasial analysis and writing manuscript. E.R. Ardli contributed to obtaining funding dan supervision. Y. Isowa designing the experimental work and data analysis. T. Kajita performed a part of data analyses.

ACKNOWLEDGEMENTS

The authors thank e-ASIA Joint Program from Endowment Fund for Education Agency (Lembaga Pengelola Dana Pendidikan), Ministry of Finance, Republic of Indonesia year 2024-2025 [019/E5/PG.02.00/PRPB BATCH 2/2024]. This study was also partly funded by the Japan Society for the Promotion of Science (JSPS) Core-to-Core Program (JPJSCCB20240006), JSPS KAKENHI Fund for the Promotion of Joint International Research (21KK0115), and Japan Science and Technology Agency (JST) (SICORP e-ASIA JPMJSC21E5 and Nature Positive Hub PMJPF2206).

CONFLICT OF INTEREST

The authors declare that they have no competing financial interests or personal relationships that may have influenced the work reported in this study.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	percent
∑	Sigma
ANOVA	Analysis of variance
BEL	Belawan
BLAST	Basic local alignment search tool
BP	Base pairs
CBMM	Community-based mangrove management
CI	Confidence interval
COI	Cytochrome oxidase Subunit
D	Distribution
DDBJ	DNA Data Bank of Japan
DNA	Deoxyribonucleic acid
E	The evenness index
ENA	European Nucleotide Archive
eDNA	Environmental deoxyribonucleic acid
F	Forward
H'	The diversity index
H'max	The maximum of diversity index
ha	Hectare
ID	Identifier
IUCN	International union for conservation of nature
iTOL	interactive tree of life
ITS	Internal Transcribed Spacer
LGS	Langsa
LK	Lubuk Kertang
M	Meter
MEGA X	Molecullar Evolutionary Genetics Analysis
MOTUs	Molecular Operational Taxonomic Units
N	Total number of individuals
Ni	Number of individuals of species i
N.loc	Total sampling locations
Ni.loc	Total number of locations
NJ	Neighbor-joining
PCR	Polymerase chain reaction
PCT	Percut Sei Tuan

Pi	The ratio of individuals of species
PS	Pulau Sembilan
rRNA	Ribosomal ribonucleic acid
R	Reverse
(R)	Richness index
S	Total number of species
WGS	Whole-genome sequencing

REFERENCES

Abidin, D.H.Z.; Nor, S.Z.M.; Lavoué, S.; Rahim, M.A.; Akib, N.A.M., (2022). Assessing a megadiverse but poorly known community of fishes in a tropical mangrove estuary through environmental DNA (eDNA) metabarcoding. Sci. Rep., 12: 16346 **(16 pages).**

Afrand, M.; Sourinejad, I.; Shahdadi, A.; Vera, M., (2024). DNA Barcoding for Identification and Discovery of Fish Species in the Protected Mangroves of Hormozgan, Iran. Estuaries Coasts. 47: 865-879 **(15 Pages)**.

Al Jufaili, S.M.; Jawad, L.A.; Park, J.M.; Al Sariri, T.S.; Al Balushi, B.Y., (2021). Fish diversity of mangrove ecosystems in Sultanate of Oman. Cah. Biol. Mar., 62(3): 235-249 **(15 pages).**

Alongi, D.M., (2018). Impact of global change on nutrient dynamics in mangrove forests. Forest. 9(10): 596 **(13 pages)**.

Ardli, E.R.; Wolff, M., (2009). Land use and land cover change affecting habitat distribution in the Segara Anakan lagoon, Java, Indonesia. Reg. Environ. Change. 9:235-243 **(9 pages)**.

Asriyana; Irawati, N.; Halili, (2020). Length-weight relationships and ponderal index of three reef fish (Teleostei: Labridae) off the Tanjung Tiram coast, Southeast Sulawesi, Indonesia. Biodiversitas. 21(4): 1279-1286 **(8 pages)**.

Ahn, H.; Kume, M.; Terashima, Y.; Ye, F.; Kameyama, S.; Miya, M.; Yamashita, Y., (2020). Evaluation of fish biodiversity in estuaries using environmental DNA metabarcoding. PLoS ONE. 15: e0231127 **(15 pages)**.

Baderan, D.W.K.; Aydalina, R.V.; Hamidun, M.S., (2023). Morphological characteristics and biodiversity of mudskipper fish (Periophthalmus: Gobiidae) in mangrove ecosystem of coastal Bay of Tomini, Boalemo, Gorontalo Province, Indonesia. Biodiversitas. 24 (1): 498- 507 **(10 pages)**.

Barreto, M.O.; Rey Planellas, S.; Yang, Y.; Phillips, C.; Descovich, K., (2022). Emerging indicators of fish welfare in aquaculture. Rev. Aquacult., 14(1): 343-361 **(18 pages).**

Basyuni, M.; Amelia, R.; Aznawi, A.A.; Wirasatriya, A.; Iryanthony, S.B.; Slamet, B.; Al Mustaniroh, A.A.; Rahmania, R.; Rahmila, Y.I.; Sumarga, E.; Larekeng, S.H.; Salmo, S.G. III.; Kajita, T.; Sivaipram, I. (2025). Reduction of mangrove carbon stock ecosystems due to illegal logging using a combination of unmanned aerial vehicle imagery and field surveys. Global J. Environ. Sci. Manage., 11(1): 41-56 **(16 pages)**.

Basyuni, M.; Sulistiyono, N.; Slamet, B.; Wati, R., (2018). Carbon dioxide emissions from forestry and peat land using land-use/land-cover changes in North Sumatra, Indonesia. IOP Conference Series: Earth Environ. Sci., 126(1): 1–6 **(6 pages).**

Basyuni, M.; Slamet, B., Sulistiyono, N., Munir, E., Vovides, A. G., & Bunting, P. (2021). Physicochemical characteristic, nutrient, and fish production in different types of mangrove forest in North Sumatra and Aceh Provinces of Indonesia. Kuwait J. Sci., 48(3): 1-14 (**14 pages**).

Basyuni, M.; Sasmito, S. D.; Analuddin, K.; Ulqodry, T. Z.; Saragi S. M. F.; Eddy, S.; Milantara, N., (2022). Mangrove Biodiversity, Conservation and Roles for Livelihoods in Indonesia. In Mangroves: Biodiversity, Livelihoods and Conservation. 397-445 Springer, Singapore. **(49 pages)**.

Basyuni, M.; Syahbana, R.; Rangkuti, A.; Pradisty, N.; Susilowati, A.; Siregar, L.; Al Mustaniroh, S.; Aznawi, A.; Mubaraq, A.; Ardli, E.; Larekeng, S.; Leopardas, V.; Isowa, Y.; Kajita, T., (2024). Mangrove plants using deoxyribonucleic acid barcodes for enhancing biodiversity and conservation. Global J. Environ. Sci. Manage., 10(3): 1391-1410 (**20 pages**).

Basyuni, M.; Wasilah, M.; Hasibuan, P.A.Z.; Sulistiyono, N.; Sumardi; Bimantara, Y.; Hayati, R.; Sagami, H.; Oku, H., (2019). Salinity and subsequent freshwater influences on the growth, biomass, and polyisoprenoids distribution of Rhizophora apiculata seedlings. Biodiversitas J. Biol. Diversity, 20(1): 288-295 **(8 pages)**.

Bhowmik, A.K.; Padmanaban, R.; Cabral, P.; Romeiras, M.M., (2022). Global mangrove deforestation and its interacting social-ecological drivers: A systematic review and synthesis. Sustainability. 14: 4433 **(25 pages)**.

Carlson, R.R.; Evans, L.J.; Foo, S.A.; Grady, B.W.; Li, J.; Seeley, M.; Xu, Y.; Asner, G.P., (2021). Synergistic benefits of conserving land-sea ecosystems. Global Ecol. Conserv., 20: e01604 **(21 pages)**.

Damastuti, E.; Groot, R.D.; Debrot, A.O.; Silvius, M.J., (2022). Effectiveness of community-based mangrove management for biodiversity conservation: A case study from Central Java, Indonesia. Trees, Forest and People. 7:100202 **(13 pages)**.

Du, J.; Xie, M.; Wang, Y.; Chen, Z.; Liu, W.; Liao,J.; Chen, B., (2020). Connectivity of fish assemblages along the mangrove-seagrass-coral reef continuum in Wenchang, China. Acta Oceanologica Sinica. 39(14): 43-52 **(10 pages)**.

Eddy, S.; Basyuni, M., (2020). Short Communication:The phenomenon ofnipah(Nypa fruticans) invasion in the Air Telang Protected Forest, Banyuasin District, South Sumatra, Indonesia. Biodiversitas. 21(11): 5114-5118 **(5 pages)**.

FAO, (2024). The state of world fisheries and aquaculture 2024 – Blue transformation in action. Rome (**264 pages**).

Fekri, L.; Analuddin, K.; Yusnaini; Adimu, H.E.; Chadijah, A., (2024). Species composition and size distribution of fishes in mangrove ecosystems in Kenari and Staring Bays, Southeast Sulawesi, Indonesia. Biodiversitas. 25(10): 3683-3692 **(10 pages)**.

Goessens, A.; Satyanarayana, B.; Stocken, T.V.D.; Zuniga, M.Q.; Lokman, H.M.; Sulong, I.; Guebas, F.D., (2014). Is Matang mangrove forest in malaysia sustainably rejuvenating after more than a century of conservation and harvesting management? PloS ONE. 9(8): e105069 **(14 pages)**.

Gostel, M.R.; Kress, W.J., (2022). The expanding role of DNA barcodes: Indispensable tools for ecology, evolution, and conservation. Diversity, 14(3): 213 **(23 pages)**.

Gregorius, H.; Gillet, E., (2022). The concept of evenness/unevenness: Less evenness or more Unevenness. Acta Biotheoretica. 70:3 **(28 pages)**.

Habib, K.A.; Neogi, A.K.; Rahman, M.; Oh, J.; Lee, Y.H.; Kim, C.G., (2021). DNA barcoding of brackish and marine water fishes and shellfishes of Sundarbans, the world's largest mangrove ecosystem. PLoS ONE. 1–17 **(17 pages)**.

Hairani, H.; Amelia, R.; Susetya, I.E.; Susilowati, A.; Bimantara, Y.; Kajita, T.; Basyuni, M., (2023). Implementa-tion of 16S rRNA Gene for Fish and Shrimp Barcoding in Mangrove Ecosystems in North Sumatra and Aceh, Indonesia. Sci. J. Fish. Mar., 15(1):152–161 **(10 pages)**.

Hammerstein, H.V.; Fett, T.M.; Ferse, S.C.A.; Helfer, V.; Kininmonth, S.; Bejarano, S., (2024). Individual mangrove trees provide alternative

reef fish habitat on backreefs. Sci. Rep., 14: 18574 **(17 pages)**.
Herrera, A.M.; Reira, R.; Rodriguez, R.A., (2023). Alpha species diversity measured by Shannon's H-index: Some misunderstandings and underexplored traits, and its key role in exploring the trophodynamic stability of dynamic multiscapes. Ecol. Ind., 156:111118 **(11 pages)**.
Hidayat, T.; Kusmana, C.; Tiryana, T., (2017). Species composition and structure of secondary mangrove forest in Rawa Timur, Central Java, Indonesia. 10(4): 675-686 **(12 pages)**.
Huang, L.; Huang, D.; Wu, Z.; Kang, B.; Chen, Z., (2016). Temporal variation of fish diversity and assemblages and their associations to environmental variables in the mangrove of Qinzhou Harbor, Guangxi Province, China. Turk. J. Fish. Aquat. Sci., 16(2): 297-310 **(14 pages)**.
Hubert, N.; Kadarusman; Wibowo, A., (2015). DNA Barcoding Indonesian Freshwater Fishes: Challenges and Prospects. DNA Barcodes. 3: 144–169 **(26 pages)**.
Imtiaz, A.; Nor, S.A.M.; Naim, D.M., (2017). Review: Progress and potential of DNA barcoding for species identification of fish species. Biodiversitas. 18(4): 1394-1405 **(12 pages)**.
Islam, M.M.; Islam, N.; Habib, A.; Mozumder, M.M.H., (2020). Climate Change Impacts on a Tropical Fishery Ecosystem: Implications and Societal Responses. Sustainability. *12*(19): 1-21 **(21 pages)**.
Isroni, W.; Sari, P.D.W; Sari, L.A.; Daniel, K.; South, J.; Islamy, R.A.; Wirabuana, P.Y.A.P.; Hasan, V., (2023). Checklist of mangrove snails (Gastropoda: Mollusca) on the coast of Lamongan District, East Java, Indonesia. Biodiversitas. 24 (3): 1676-1685 **(10 pages)**.
Jennerjahn, C.; Ardli, E.R.; Boy, J.; Heyde, J.; Lukas, M.C.; Nordhaus, I.; Sastranegara, M.H.; Máñez, K.S.; Yuwono,E., (2023). Mangrove ecosystems under threat in Indonesia: the Segara Anakan Lagoon, Java, and other examples. Science for the Protection of Coastal Ecosystems. Chapter 7 251-284 **(35 pages)**.
Kadim, M. K.; Pas, N.; Alinti, E. R.; Panigoro, C., (2022). Biodiversity and community assemblages of freshwater and marine macrozoobenthos in Gorontalo Waters, Indonesia. Biodiversitas J. Biol. Divers., 23(2): 637-647 **(11 pages)**.
Keck, F.; Couton, M.; Altermatt, F., (2022). Navigating the seven challenges of taxonomic reference databases in metabarcoding analyses. Mol. Ecol. Resour., 23(4): 742-755 **(14 pages)**.
Khan, M.F.A.; Rahman, M.S.; Giessen, L., (2020). Mangrove forest policy and management: Prevailing policy issues, actors' public claims and informal interests in the Sundarbans of Bangladesh. Ocean Coast. Manage., 186: 105090: 1-14 **(14 pages)**.
Kumar, S.; Stecher, G.; Li, M., Knyaz, C., Tamura, K., (2018) MEGA X: molecular evolutionary genetics analysis across computing platforms. Mol. Biol. Evol. 35(6):1547-1549 **(3 pages)**.
Laojun, S.; Changbunjong, T.; Chaiphongpachara, T., (2023). Evaluation of modern techniques for species identification of *Lutzia Mosquitoes* (Diptera: Culicidae) in Thailand: Geometric morphometrics and DNA barcoding. Insects. 14(78) **(16 pages)**.
Letunic, I.; Bork, P., (2024). Interactive Tree of Life (iTOL) v6: recent updates to the phylogenetic tree display and annotation tool. Necleic Acids Res., 52(1): 78-82 **(7 pages)**.
Nagelkerken, I.; Goldenberg, S.U.; Coni, E.O.C.; Connell, S.D., (2018). Microhabitat change alters abundances of competing species and decreases species richness under ocean acidification. Sci. Total Environ., 645: 615–622 **(8 pages)**.
Nur, F.M.; Batubara, A.S.; Fadli, N.; Rizal, S.; Siti-Azizah, M.N.; Muchlisin, Z.A., (2021). Diversity, distribution, and conservation status of Betta fish (Teleostei: Osphronemidae) in Aceh waters, Indonesia. Europ. Zool. J., 89(1): 142-151 **(10 pages)**.
Nordhaus, I.; Toben, M.; Fauziyah, A., (2019). Impact of deforestation on mangrove tree diversity, biomass and community dynamics in the Segara Anakan lagoon, Java, Indonesia: A ten-year perspective. Estuarine, Coastal Shelf Sci., 227: 106300 **(12 pages)**.
Pandiangan, P.; Basyuni, M.; Slamet, B.; Putri, L.A.P., Wati, R. (2024). Structure and composition of rehabilitated mangrove in Lubuk Kertang Village, North Sumatra, Indonesia. IOP Conf. Series: Earth Environ. Sci., 36(1): 123-134 **(12 pages)**.
Pagano, M.; Gauvreau, K.; Mattie, H., (2022). Principles of biostatistics. Chapman and Hall/CRC **(620 pages).**
Pasquaud, S.; Vasconcelos, R.P.; França, S.; Henriques, S.; Costa, M.J.; Cabral, H., (2015). Worldwide patterns of fish biodiversity in estuaries: Effect of global vs. local factors. Estuarine Coast. Shelf Sci., 154 **(12 pages)**.
Phukuntsi, M.A.; Brettschneider, H.; Dalton, D.L.; Kearney, T.; Badenhorst, J.; Kotze, A., (2016). DNA barcoding for identification of cryptic species in the field and existing museum collections: a case study of *Aethomys* and *Micaelamys* (Rodentia: Muridae). Afr. Zoo., 51(1): 69-76 **(8 pages).**
Purwanto, R.H.; Mulyana, B.; Satria, R.A.; Yasin, E.H.E.; Putra, I.S.R.; Putra, A.D., (2022). Spatial distribution of mangrove vegetation species, salinity, and mud thickness in mangrove forest in Pangarengan, Cirebon, Indonesia. Biodiversitas, 23(3): 1384-1392 **(9 pages)**.
Ram, M.A.; Caughlin, T.T.; Roopsind, A., (2021). Active restoration leads to rapid recovery of aboveground biomass but limited recovery of fish diversity in planted mangrove forests of the North Brazil Shelf. Restor. Ecol., 29(5): e13400 **(12 pages)**.
Rejeki, S.; Debrot, A.O.; van den Brink, A.M.; Ariyati, R.W.; Lakshmi Widowati, L., (2021). Increased production of green mussels (Perna viridis) using longline culture and an economic comparison with stake culture on the north coast of Java. Indonesia. Aquacult. Res. 52, 373–380 **(8 pages)**.
Ridlo, I.A.; Kurniawan, N.; Retnaningdyah, C., (2020). Communities structure of fish in some mangrove ecosystem as a result of the restoration in southern beach of malang, East Java Indonesia. In J. Phys. Conf. Ser., 1665(1): 012020 **(7 pages).**
Rumondang, A.L.; Kusmana, C.; Budi, S.W., (2021). Species composition and structure of Angke Kapuk Mangrove Protect Forest, Jakarta, Indonesia. Biodiversitas. 22(9): 3863-3871 **(9 pages)**.
Salinas, L.; Cárdenas, P.; Graham J.P.; Trueba, G., (2024.) IS26 drives the dissemination of blaCTX-M genes in Ecuadorian community. Am. Soc. Microbiol., 12(1) **(15 pages)**.
Samal, P.; Srivastava, J.; Charles, B.; Singarasubramanian, S.R., (2023). Species distribution models to predict the potential niche shift and priority conservation areas for mangroves (*Rhizophora apiculata, R. mucronata*) in response to climate and sea level fluctuations along coastal India. Ecol. Indic., 154: 110631 **(16 pages)**.
Sari, A.; Tuwo, A.; Saru, A.; Rani, C., (2022). Diversity of fauna species in the mangrove ecosystem of Youtefa Bay Tourism Park, Papua, Indonesia. Biodiversitas. 23(9): 4490-4500 (**11 pages**).
Sasmito, S.D.; Basyuni, M.; Kridalaksana, A.; Sasmito, M.F.S.; Lovelock, C.E.; Murdiyarso, D., (2023). Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves. Nat. Ecol. Evol., 7(1): 62–70 **(9 pages).**
Setiyaningrum, I.F.; Puspitasari, E.D., (2022). Environmental analysis of mangrove ecosystems in the southern coast of Purwodadi Subdistrict, Purworejo Regency, Central Java. J. Environ. Sustainability. 6(2): 157-173 **(17 pages)**.
Seemann, J.; Yingst, A.; Stuart-Smith, R.D.; Edgar, G.J.; Altieri, A.H.,

(2018). The importance of sponges and mangroves in supporting fish communities on degraded coral reefs in Caribbean Panama. PeerJ. 6: e4455 **(22 pages).**

Setiawan, H.; Mursidin. (2018). Ecological characteristic and health of mangrove forest at Tanakeke Island South Sulawesi. 7(1):47-58 **(12 pages)**.

Sheth, B.P.; Thaker, V.S., (2017). DNA barcoding and traditional taxonomy: an integrated approach for biodiversity conservation. Genome. 60(7): 618-628 **(11 pages).**

Sheaves, M.; Baker, R.; Nagelkerken, I.; Connolly, R.M., (2015). True Value of Estuarine and Coastal Nurseries for Fish: Incorporating Complexity and Dynamics. Estuaries Coasts. 38(2): 401-414 **(14 pages)**.

Sholiqin, M.; Pramadaningtyas, P.S.; Solikah, I.; Febriyanti, S.; Pambudi, M.D.; Mahartika, S.B.; Umam, A.F., Liza, N.; Setyawan, A.D., (2021). Analysis of the diversity and evenness of mangrove ecosystems in the Pacitan Coast, East Java, Indonesia. Int. J. Bonorowo Wetlands. 11(2): 84-94 **(9 pages)**.

Wahyudewantoro, G., (2018). Freshwater fishes of Western Indonesia and Sulawesi. Biodiversitas. 19(1): 71-76 **(6 pages)**.

Wasik, S.; Pattison, R., (2024). Artificial intelligence applications in fish classification and taxonomy: Advancing our understanding of Aquatic Biodiversity. Fish Taxa. 31: 11-21 **(11 pages)**.

Wibowo, A.; Sloterdijk, H.; Ulrich, S.P., (2015). Identifying Sumatran peat swamp fish larvae throught DNA barcoding, evidence of complete life history patter. Procedia Chem., 14: 76-84 **(9 pages)**.

Widodo, P.; Herawati, W.; Hidayah, H. A.; Chasanah, T.; Proklamasiningsih, E., (2020). Distribution and Characteristics of Nypa Palm (*Nypa fruticans* Wurmb.) in Southern Part of Cilacap Regency. In IOP Conference Series: Earth Environ. Sci., 550(1): 012010 **(8 pages)**.

Winn, N.A.; Sandi, P.; Khine, T.; Nyunt, K.T.; Kyaw, H.T.; Sabai, M.; Aung, T.T.N., (2021). Effect of seasonal variation in fish species composition, abundance and diversity of Sunye Lake, Mandalay Region, Myanmar. Iran J. Ichthyol. 8(3): 204-222 **(19 pages)**.

Yun, W. Y.; Yeok, F. S.; Youshao, W.; Lu, D.; Limi, M.; Lai, G. T. (2022). Spatiotemporal dispersal study of mangrove Avicennia marina and Rhizophora apiculata propagules. Sains Malaysiana. 51(8): 2351-2364 **(14 pages)**.

Zhang, M.; Zou, Y.; Xiao, S.; Hou, J., (2023). Environmental DNA metabarcoding serves as a promising method for aquatic species monitoring and management: A review focused on its workflow, applications, challenges and prospects. Mar. Pollut. Bull., 194: 115430 **(12 Pages)**.

AUTHOR (S) BIOSKETCHES

Basyuni, M., Ph.D., Professor, Center of Excellence for Mangrove, Universitas Sumatera Utara, Jalan Perpustkaan No. 3A, Medan 20155, Indonesia.
- Email: *m.basyuni@usu.ac.id*
- ORCID: 0000-0003-1120-8571
- Web of Science ResearcherID: D-8537-2015
- Scopus Author ID: 15055287200
- Homepage: https://puimangroveusu.id/

Irmawati, Ph.D., Lecturer, Faculty of Marine Science and Fisheries, Universitas Hasanuddin, Makassar 90245, Indonesia.
- Email: *irmawati@unhas.ac.id, trif.ahwa@gmail.com*
- ORCID: 0009-0002-9739-3199
- Web of Science: JWO-1574-2024
- Scopus ID: 57194702752
- Homepage: https://fikp.unhas.ac.id/2010/03/dosen-prodi-msp/

Mubaraq, A., Ph.D. Candidate, Doctoral Program of Agriculture Science, Faculty of Agriculture, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *alfian@students.usu.ac.id*
- ORCID: 0009-0005-9810-3896
- Web of Science: JTU-5714-2023
- Scopus ID: 59122664800
- Homepage: https://www.usu.ac.id/

Susilowati, A., Ph.D., Professor, Center of Excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia
- Email: *arida.susilowati@usu.ac.id*
- ORCID: 0000-0001-9608-4787
- Web of Science: AAF-6384-2021
- Scopus ID: 56102433700
- Homepage: https://www.usu.ac.id/id/direktori/arida-susilowati

Rangkuti, A.B., M.Sc., Lecturer, Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: baiqunirangkuti@usu.ac.id
- ORCID: 0000-0002-3019-6038
- Web of Science: GPK-3826-2022
- Scopus ID: 57211799613
- Homepage: https://www.usu.ac.id/id/direktori/ahmad-baiquni-rangkut

Desrita., M.Si, Ph.D. Candidate, Department of Aquatic Resources Management, Faculty of Agriculture, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *desrita@usu.ac.id*
- ORCID: 0000-0002-1935-8294
- Web of Science: AFR-6165-2022
- Scopus ID: 57156632300
- Homepage: https://fp.usu.ac.id/id/dosen/desrita

AUTHOR (S) BIOSKETCHES

Aznawi, A. A. Ph.D. Candidate, Doctoral Program of Agriculture Science, Faculty of Agriculture, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email : aznanaznawi@students.usu.ac.id
- ORCID : 0009-0000-5801-4702
- Web of Science ResearcherID: NA
- Scopus Author IDE: 59123096500
- Homepage: https://www.usu.ac.id/

Mustaniroh, S.S., S.Si.**,** Researcher, Center of Excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: shofiyahsabilah@gmail.com
- ORCID: 0009-0000-0370-1759
- Web of Science: NA
- Scopus ID: 57972470900
- Homepage: https://www.usu.ac.id/

Larekeng, S.H., Ph.D., Professor, Biotechnology and Tree Breeding Laboratory, Faculty of Forestry, Universitas Hasanuddin, Makassar 90245, Indonesia.
- Email: sittihalimah@unhas.ac.id
- ORCID: 0000-0002-9749-9500
- Web of Science: NA
- Scopus ID: 57200256258
- Homepage: https://bachelor.forestry.unhas.ac.id/dosen/

Salman, A.H., S.Hut., Biotechnology and Tree Breeding Laboratory, Faculty of Forestry, Universitas Hasanuddin, Makassar 90245, Indonesia .
- Email: alihasansalman@unhas.ac.id
- ORCID: 0009-0003-7113-1606
- Web of Science: NA
- Scopus ID: NA
- Homepage: https://forestry.unhas.ac.id/

Ardli, E.R., Ph.D., Associate Professor, Faculty of Biology, Universitas Jenderal Soedirman, Purwokerto Utara, Banyumas 53122, Central Java, Indonesia**.**
- Email: erwin.ardli@unsoed.ac.id
- ORCID: 0000-0003-0407-0017
- Web of Science: AAD-9177-2021
- Scopus ID: 25227455500
- Homepage: http://v2.pasca.unsoed.ac.id/dr-rer-nat-erwin-riyanto-ardli-s-si-m-sc/

Isowa, Y., Ph.D., Research Associate, Iriomote Station, Tropical Biosphere Research Center, University of the Ryukyus, Taketomi, Okinawa, 907-1541, Japan.
- Email: isowa@lab.u-ryukyu.ac.jp
- ORCID: 0009-0009-5733-4355
- Web of Science: NA
- Scopus ID: 55341544900
- Homepage: https://tbc.skr.u-ryukyu.ac.jp/iriomote/staf

Kajita, I., Ph.D., Professor, Iriomote Station, Tropical Biosphere Research Center, University of Ryukyus, Takenomi, Okinawa, 907-1541, Japan.
- Email: kajita@mail.ryudai.jp
- ORCID: 0000-0003-1232-4179
- Web of Science: ABB-2784-2020
- Scopus ID: 7006291795
- Homepage: http://nesseiken.info/

HOW TO CITE THIS ARTICLE

Basyuni, M.; Irmawati; Mubaraq, A.; Susilowati, A.; Rangkuti, A.B.; Desrita; Aznawi, A.A.; Musatniroh, S.; Larekeng, S.H.; Salman, A.H.; Ardli, E.R.; Isowa, Y.; Kajita, I. (2025). Morphological and molecular monitoring of fish in the water of mangrove ecosystems. Global J. Environ. Sci. Manage., 11(2): 711-732.

DOI: 10.22034/gjesm.2025.02.19

URL: https://www.gjesm.net/article_721978.html

Global J. Environ. Sci. Manage. 11(2): 733-746, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Sustainable pest management with citronella oil for eco-friendly control of *Aphis gossypii* in chili plants

M. Istianto[1], K.D. Sutanto[1,*], S. Ikawati[2], R.C. Wicaksono[1], S. Widyaningsih[1], M.E. Dwiastuti[1], U. Triasih[1], O. Endarto[1], Affandi[1], Handoko[1], I. Yustina[3], L. Mufidah[4], S. Wuryantini[1], Nurjanani[1], S. Agustini[1], D. Setyorini[5], D.W. Utami[1]

[1] *Research Center for Horticulture, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor, Cibinong, Indonesia*

[2] *Department of Plant Pests and Diseases, Faculty of Agriculture, Brawijaya University. Jl. Veteran, Malang 65145, East Java, Indonesia*

[3] *Directorate for Scientific Collection Management, National Research and Innovation Agency Jl. M.H. Thamrin 10340, Indonesia*

[4] *Research Center for Behavioral and Circular Economics, National Research and Innovation Agency. PPID Building, Jl. Jend. Gatot Subroto, Jakarta Selatan, Indonesia*

[5] *Research Center for Estate Crops, National Research and Innovation Agency Jl. Raya Jakarta-Bogor, Cibinong, Indonesia*

ARTICLE INFO

Article History:
Received 07 November 2024
Revised 11 January 2025
Accepted 14 March 2025

Keywords:
Botanical pesticide
chilli aphid
Cymbopogon nardus
Pest control
Toxicity

ABSTRACT

BACKGROUND AND OBJECTIVES: Chili is a key agricultural commodity in Indonesia, yet its productivity remains low, primarily due to pest and disease infestations. One of the most detrimental pests to chili plants is *Aphis gossypii*. While insecticides are effective in managing these pests, their environmental impact raises concern, making it essential to explore eco-friendly options. Citronella oil, a potential natural pesticide, warrants further investigation. This study was conducted in both laboratory and field settings. In the laboratory, the efficacy of citronella oil in controlling *Aphis gossypii* was assessed in terms of its toxicity and repellent effects. This study focused on analyzing the efficacy of citronella oil in regulating the populations of *Aphis gossypii* on chili plants.

METHODS: Laboratory and field experiments employed a Randomized Block Design. In the laboratory, citronella oil concentrations were tested against a control, and both mortality and repellent effects were monitored. In the field study, four treatments were implemented: the use of citronella oil, rotation with synthetic insecticides, and a control condition. The *Aphis gossypii* population was assessed weekly for a duration of ten weeks.

FINDINGS: The results revealed that citronella oil effectively reduced *Aphis gossypii* populations, demonstrating repellent (18.6 percent) and toxic (89.1 percent) effects. Citronella oil demonstrated a reduction in *Aphis gossypii* populations under field conditions, both when utilized on its own and when rotation with synthetic insecticides. At the end of the observation period, a single application of citronella oil resulted in a 91 percent reduction in *Aphis gossypii* populations. Citronella oil stands out as a sustainable and efficient method for controlling *Aphis gossypii*, making it a promising substitute for conventional insecticides in the management of pests affecting chili plants.

CONCLUSION: This study demonstrates that citronella oil effectively reduces *Aphis gossypii* infestations on chili plants by repelling and intoxicating the pests acting as a natural pesticide, citronella oil presents a safer alternative to synthetic chemicals, thereby decreasing environmental pollution and protecting beneficial organisms. Its integration into pest management strategies has the potential to promote sustainable agricultural practices. However, further research is needed to validate its effectiveness across different locations and assess its broader ecological impact.

DOI: 10.22034/gjesm.2025.02.20

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
40	4	5

*Corresponding Author:
Email: *koko006@brin.go.id*
Phone: +62857 0018 5612
ORCID: 0000-0002-3605-4954

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Chili is a key agricultural commodity within Indonesia's horticulture subsector, playing a vital role in supporting the national economy, particularly through its contribution to increasing household income. The average chili production across the nation in 2022 was 7.2 tons per hectare, a figure that falls well short of the potential yield range of 15 to 20 tons per hectare (ha) (BPS, 2023). One of the main causes of this yield gap is the infestation of plant pests and diseases. The primary pests affecting chili plants are fruit flies (*Bactrocera s* Macquart (Diptera: Tephritidae) (Jamaluddin *et al.,* 2020), aphids (*Aphis gossypii* Glover (Hemiptera: Aphididae)) (Jamaluddin *et al.,* 2020) and silverleaf whitefly (*Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) (Saad *et al.,* 2017). *Aphis gossypii* is a pest and disease vector in chili plants (Cocuzza, 2024). The viruses transmitted by this insect are cucumber mosaic virus (CMV) and potato virus Y (PVY) (Thangjam *et al.,* 2023; Milonas *et al.,* 2023). Many farmers utilize synthetic chemical pesticides as their primary strategy for pest control (Agarwal and Verma, 2021), yet these substances are often used in ways that are misguided and. These inaccuracies span across factors such as dosage, concentration, application timing, and frequency, all of which lead to negative consequences, including the development of pest resistance (Özkara *et al.,* 2016; Siddiqui *et al.,* 2023), loss of beneficial insects (Siviter and Muth, 2020), environmental pollution and health problems (Pathak *et al.,* 2022). As resistance develops, there is a corresponding rise in the amount of insecticide used, since the recommended levels no longer succeed in controlling pests (Sarwar and Salman, 2015). Since synthetic insecticides are the main approach for managing Aphis gossypii in chili plants, it is essential to mitigate the adverse effects linked to their regular application. Efforts should focus on minimizing synthetic insecticide applications. This goal can be accomplished by implementing cutting-edge research methods to create a comprehensive insecticide application model that merges synthetic pesticides with plant-based alternatives (Wiratno *et al.,* 2025). The key component of this model is the use of citronella oil as a botanical pesticide, which aims to reduce reliance on synthetic chemicals while maintaining effective pest control. Citronella oil was chosen as a botanical pesticide due to previous studies showing that essential oils, including citronella, have harmful effects on insect pests (Istianto and Emilda, 2021); (Wicaksono *et al.,* 2023). Citronella oil in suppressing pest populations, functions as an insecticide (Saad *et al.,* 2017) egg-laying inhibitor, anti-feedant (Saleh *et al.,* 2023), and insect repellent (Saad *et al.,* 2017; Fouda *et al.,* 2017). The results of this study are anticipated to create avenues for the integration of plant-based materials into pest management strategies, thereby fostering more environmentally sustainable control practices. This study was carried out in both laboratory and field settings. In the laboratory, the efficacy of citronella oil in controlling *Aphis gossypii* was assessed in terms of its toxicity and repellent effects at Brawijaya University in Malang, East Java, Indonesia. The objective of this research was to assess the effectiveness of citronella oil in managing *A. gossypii* on chili plants while decreasing dependence on chemical pesticides. In Indonesia, the application of citronella oil as a botanical pesticide remains limited. Therefore, assessing its effectiveness and mode of action against this pest is essential. This study has been carried out in Tlekung Village, Batu City, Indonesia in 2023.

MATERIALS AND METHODS

Location and Time

Field research was conducted on chili plantations located on farmers' land in Tlekung Village, Batu City, 950 meters above sea level (masl) 7°54'19.5" south (S), 112°32'07.6" east (E) (Fig. 1). The climate conditions of Batu City include an average relative humidity of 77%, an average temperature of 24 degrees Celsius (°C), and average rainfall of 170 cubic meters (mm^3). The soil type in this area is andosol.

Analysis of compounds contained in citronella oil

For the testing, the citronella oil was procured from a supplier based in in Batusangkar, West Sumatra. Gas chromatography–mass spectrometry (GC-MS) analysis of the essential oil was conducted using a Shimadzu GC-2010 Plus gas chromatograph at the Instrumentation Laboratory of the Chemistry Department, FMIPA, Brawijaya University, Malang, East Java. The analysis was performed over a 50-minute period. A TG-5MS capillary column as 30 meters (m) length, 0.2 millimeters (mm) inner diameter, 0.25 micrometers (µm) film thickness, was used. A total of 2 microliters (µL) of the essential oil was injected into the GC apparatus.

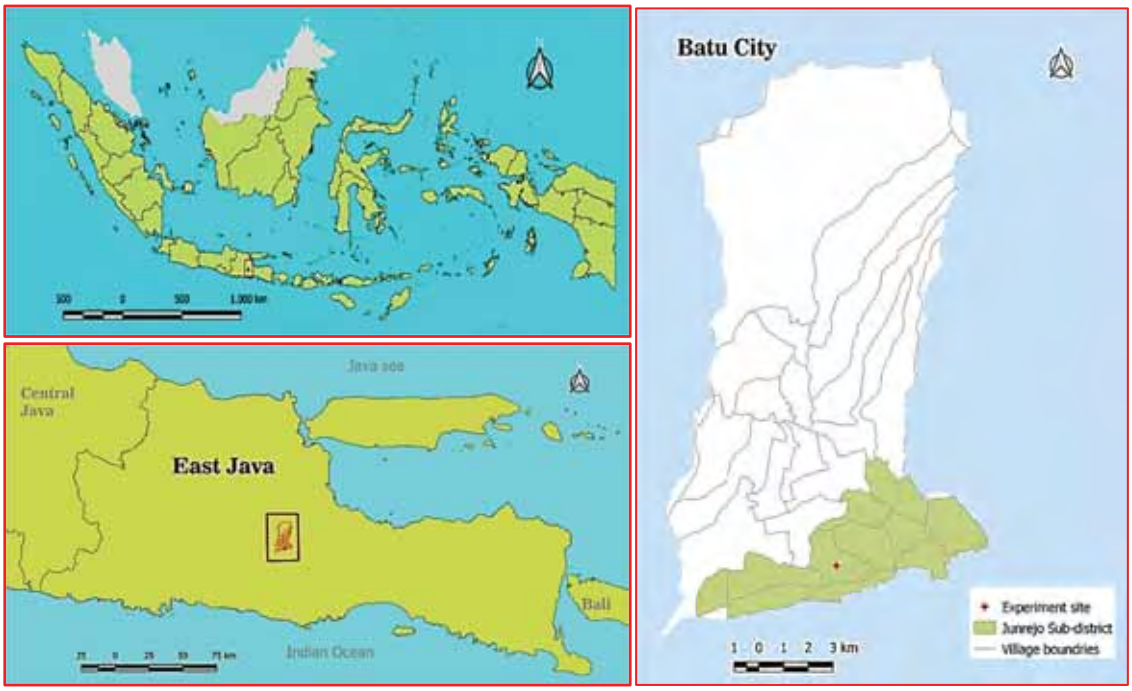


Fig. 1: Geographical location of the study area in the Brawijaya University in Malang, Indonesia

Laboratory study

The objective of the laboratory study was to assess how effective citronella oil is in managing *A. gossypii*. This study concentrated on analyzing the toxic and repellent characteristics of citronella oil, identifying them as the primary methods of combating this insect.

Tests on citronella oils toxicity against A. gossypii

In this test, the applied treatments were concentrations of pure citronella oil of (a) 1 milliliter per liter (mL/L), (b) 2 mL/L, (c) 3 mL/L, (d) positive control (abamectin insecticide), and (e) negative control (water, emulsifier). To improve the oil's dissolution in the water, an emulsifier was introduced at a concentration of 1 mL/L. Each treatment was repeated six times. A randomized block design (RBD) was applied, with treatment time serving as the block or replication. The population of *Aphis gossypii* per sample unit was set at 20 individuals. The study began by collecting shoot clusters or young leaves of chili, which were then hand-sprayed with a 3 milliliters (mL) treatment solution. Once the leaves had been sprayed, they were allowed to dry and then transferred into 2 mL glass bottles containing water, making sure that the leafstalks were immersed. To ensure the leaves remained fresh, a soaking procedure was carried out. The glass bottles with the leaves were then placed into 100 mL plastic vials for additional examination. The leaves function as food for *A. gossypii* (Nindatu *et al.,* 2018). A total of 20 *A. gossypii* imagoes were placed into each plastic vial, which were then sealed with ventilated lids covered in gauze. The vials were equipped with a layer of filter paper at the bottom, which was saturated with the treatment solution based on the test concentration. This setup ensured that the pests maintained contact with the test material even when they were not on the leaves. The setup for the toxicity test is illustrated in Fig. 2. Observations were made on the number of insect individuals that died at the following time intervals: 1, 2, 3, 6, 12, 24, and 48 hours (h) post-application.

The mortality percentage of the *A. gossypii* was calculated using Eq. 1 (Hidayati *et al.,* 2013):

$$Po = a/b \times 100\% \quad (1)$$

Where,

Po= mortality percentage; a = number of dead *A. gossypii*; b = number of *A. gossypii* in the treatment

If mortality occurs in the control group, the

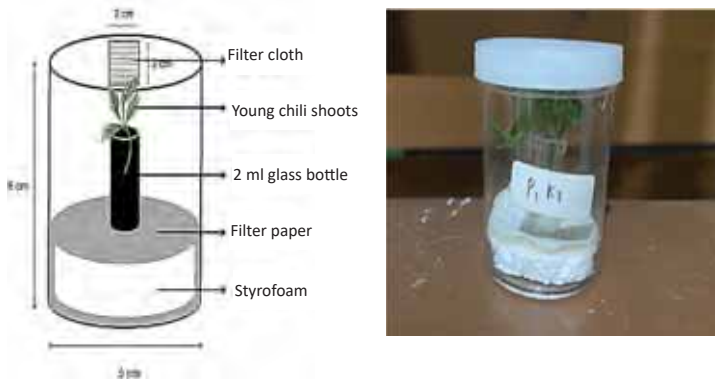


Fig. 2: Container for toxicity test

mortality percentage must be corrected. If the mortality in the control exceeds 20%, the test must be repeated (Matsumura, 2012). The corrected mortality percentage is calculated using Eq. 2 (Abbott, 1925):

$$E = C\text{-}T/C \times 100\% \quad (2)$$

Where,
E= mortality percentage; C= Quantity of insects that survived under the control; T= quantity of insects that survived the treatment.

Tests of citronella oils repellence against A. gossypii

The repellence test used the Petri Dish Olfactometer (Ikawati *et al.,* 2017). The olfactometer was modified by using 9 centimeters (cm) diameter Petri dishes, each with two vials attached to the bottom. Two holes, each measuring 2.5 cm in diameter to correspond with the size of the vials, were created in the Petri dishes. The holes were spaced approximately 3 cm apart, with the distance from the bottle hole to the rim of the dish being 1 cm. The vials, made of plastic, had a height of 3.5 cm. The Petri dish lids were altered to include a 2 cm diameter opening, which was covered with gauze to ensure that the insects could not escape. This configuration is depicted in Fig. 3.

This study began by selecting two clusters of chili shoots or young leaves. One cluster was treated with a solution of citronella oil, which included water, essential oil, and an emulsifier, while the other cluster received only water as a control treatment. The citronella oil concentrations tested were 1 mL/L, 2 mL/L, and 3 mL/L. The experimental design was a randomized block design, with treatment time serving as the block or replication. Each treatment was repeated seven times. After being sprayed, the clusters were air-dried for three minutes before being placed into separate vials. These vials were then affixed to the bottoms of Petri dishes. For each iteration, 20 adult *A. gossypii* were placed in the center of the Petri dishes, and the dishes were sealed. The number of *A. gossypii* adults entering vials with either citronella oil-treated or control clusters of shoots or young leaves was recorded at1, 2, and 3 hours post-application. In the repellence test, the number of *A. gossypii* entering the treated vials was compared to the number entering the control vials, using Eq. 3 (Pascual-Villalobos and Robledo's (1998):

$$R.I. = (C-T/C+T) \times 100 \quad (3)$$

Where,
RI: repellence index (%); C: quantity of insects in the control; T: quantity of insects in the treatment

In assessing the repellency properties, Pascual-Villalobos and Robledo (1998) stated that positive IR values indicate repellent properties, while negative IR values suggest attractant properties. The assessment of repellency is conducted according to the criteria presented in Table 1.

The data obtained were analyzed using analysis of variance (ANOVA) with Minitab 17. When substantial differences were identified among treatments, post hoc comparisons were performed using the Tukey test. A treatment difference was considered statistically significant when the p-value was 0.05 or lower

Field study

The purpose of the field study was to evaluate the

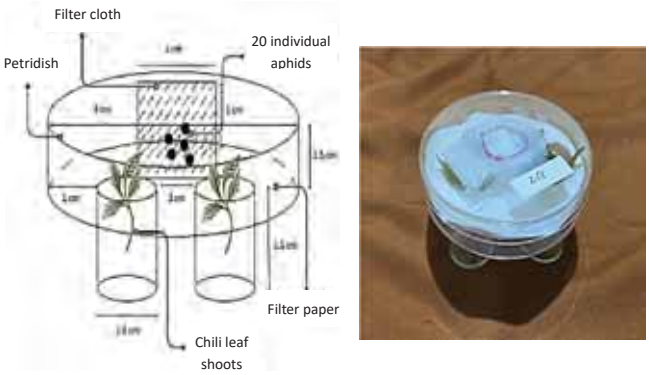


Fig. 3: Container for repellence test of *A. gossypii*

Table 1: Repellence level criteria

Repellence class	Repellence level	Repellence index (%)
0	Weak	<0.1
I	Moderately weak	0.1-20
II	Medium	20.1-40
III	Moderately strong	40.1 -60
IV	Strong	60.1-80
V	Very strong	80.1-100

effectiveness of a rotation pattern using citronella oil and synthetic insecticides in controlling *Aphis gossypii* on chili plants. The interventions were as follows: (a) a weekly application of citronella oil, (b) a weekly rotation between citronella oil and synthetic insecticides, (c) a weekly application of synthetic insecticides, and (d) a control group that received no treatment. The first application of treatments was conducted one week after planting. A randomized block design was used as the experimental design. The concentration of citronella oil was set at 2 mL/L, based on findings from previous studies (Istianto and Emilda, 2021). Pure citronella oil was used, and an emulsifier (Alkylaryl polyglycol ether, 400 grams per liter (g/L) active ingredient) was added to ensure proper dissolution in water, with a concentration of 1 mL/L of water. Abamectin, a synthetic pesticide, was employed at a dosage of 1 mL/L of active ingredient. Each treatment was replicated four times. Over a span of ten weeks, weekly evaluations of the *A. gossypii* population on each chili plant were performed. These evaluations were conducted the day before pesticide treatments were applied.

RESULTS AND DISCUSSION

This study points out that the field experiments, which were performed in one region with specific climate conditions and for a limited time, might not completely represent long-term and seasonal fluctuations. Thus, it is important to implement trials in various locations and across different seasons to ensure broader validation.

Compounds present in the scented oil of citronella oil

GC-MS analysis identified several bioactive compounds in citronella oil. The main compounds contained in citronella oil were alpha terpinolene, citronella, citronellyl acetate, Cyclohexane, 1-ethenyl-1-methyl-2,4-bis(1-methylethenyl)-, Cyclohexene, 1-methyl-4-(1-methylethenyl), E-citral, geranyl acetate, germacrene D, trans-caryophyllene, and Z-citral The analysis's findings are displayed in Fig. 4 and Table 2. The insecticidal and repellent characteristics of citronella oil are attributed to these compounds. Previous studies have confirmed that citronellal and citronellol disrupt insect nervous systems, leading to paralysis and mortality (Ken *et al.,* 2005). On a molecular level, the bioactive substances found in citronella oil hinder neurotransmission and metabolic activities, which results in diminished feeding behavior and eventual mortality in insect pest (Chaudhari *et al.,* 2021). Additionally, geranyl

acetate has been shown to interfere with insect respiration and feeding behavior (Angelica *et al.,* 2020). Compared to many synthetic pesticides, citronella oil has a lower toxicity level for beneficial insects. Nonetheless, more comparative studies involving other natural products are required to thoroughly understand its selectivity and ecological consequences (Nerio *et al.,* 2010). The presence of these compounds highlights citronella oil's potential as a natural pesticide with multiple modes of action. Citronella oil's effectiveness as a repellent and its toxic characteristics stem from several key bioactive compounds, including citronellal, citronellol, geranyl acetate, and limonene. These substances interfere with neural signaling and olfactory perception in *Aphis gossypii* (Popescu *et al.,* 2024). The dual repellent and insecticidal actions of citronella oil effectively reduce pest populations and may offer long-term benefits by delaying resistance development, thereby supporting sustainable pest management (Rattan, 2000). Prolonged and repeated use of citronella oil could impact the health of chili plants, the composition of soil microbial communities, and non-target organisms. Therefore, additional multi-season research is required to assess any potential phytotoxic and ecological consequences (Lahlali *et al.,* 2022). The findings of this study demonstrate that citronella oil has a detrimental effect on *Aphis gossypii*, both killing and repelling the pests, thereby reducing their population in the field. This observation aligns with previous studies that have shown citronella oil's efficacy in causing mortality in other pests, such as *Aedes aegypti*. These reliable results underscore the potential of citronella oil as an effective agent for pest management, specifically targeting (Cansian *et al.,* 2023; Cansian, 2021), *Oryzaephilus surinamensis* (Gharsan *et al.,* 2022) and *Spodoptera frugiperda* (Saleh *et al.,* 2023). Likewise, the repellent properties

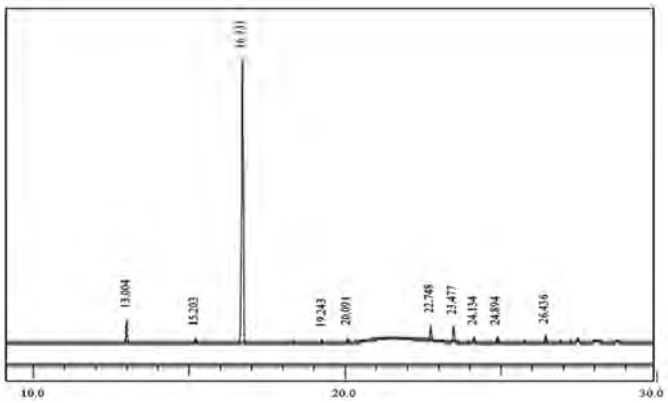


Fig. 4: Results of compound identification analysis in citronella oil using GC-MS

Table 2: The substances found in citronella oil

No.	Substances	R. Time	m/z	Area	Height	Conc.	UnitR	Index
1	Alpha terpinolene	15.203	43.00	80550	20613	0.582	%	0
2	Citronella	16.731	41.00	11934500	2967389	86.206	%	0
3	Citronellyl acetate	22.748	43.00	316898	102373	2.289	%	0
4	Cyclohexane, 1-ethenyl-1-methyl-2,4-bis(1-methylethenyl)-	24.134	41.00	42581	15675	0.308	%	0
5	Cyclohexene, 1-methyl-4-(1-methylethenyl)-	13.004	68.00	538175	181666	3.887	%	0
6	E-Citral	20.091	41.00	171085	52632	1.236	%	0
7	Geranyl acetate	23.477	69.00	462168	145319	3.338	%	0
8	Germacrene D	26.436	41.00	104461	29957	0.755	%	0
9	trans-Caryophyllene	24.894	41.00	107077	33742	0.773	%	0
10	Z-Citral	19.243	41.00	86637	27960	0.626	%	0

of citronella oil were also seen when it was tested on other pests such as *Bemisia tabaci* (Saad *et al.,* 2017), *Ceratitis* capitata (Gonzaga *et al.,* 2023) and Arthropoda (Lee, 2018).

Population dynamics of A. gossypii in the treatments of citronella oil and insecticide application

Findings from the study reveal that the application of citronella oil, either alone or in conjunction with synthetic insecticides on a weekly schedule, significantly reduces the Aphis gossypii population more effectively than the control group that received no treatment. The control treatment was included to monitor the natural presence and population dynamics of the pest in the absence of any control measures. Each treatment demonstrates varying levels of effectiveness in controlling the population of *Aphis gossypii*. Under field conditions, citronella oil deteriorates fairly quickly, making it essential to reapply it on a weekly basis to ensure ongoing effectiveness in pest management (Isman, 2006). Table 3 presents the results of ANOVA, which was conducted to assess the efficacy of each treatment in reducing the insect population.

In the second week of observation, following two applications, a marked difference was noted in the ability of the sole citronella oil treatment (P4) to suppress the *A. gossypii* population compared to the control group. This contrasts with other treatments, where a noticeable reduction in pest numbers compared to the control was achieved in the fifth week for the P2 treatment and in the third week for the K+ treatment. In subsequent weeks, the pesticide application treatments (P2, P4, and K+) continued to effectively suppress the pest population until the tenth week. Trials conducted in the field revealed that citronella oil significantly controls the populations of *A. gossypii*. The sole application of citronella oil (P4) led to a 91% reduction in aphid populations by the tenth week, comparable to the synthetic insecticide treatment (K+). This aligns with findings from Saad *et al.* (2017), who reported significant pest reduction when citronella oil was applied to whitefly populations. The treatment that combined citronella oil with synthetic insecticides (P2) showed superior effectiveness in lowering aphid populations compared to using synthetic insecticides by themselves. The data indicate that the integration of citronella oil into IPM can enhance crop yield and quality by reducing pest-related damage, though additional comparative analyses are necessary (Istianto and Emilda, 2021). Early analyses of synergy reveal that citronella oil can be effectively paired with other botanical pesticides and biological control agents, which may enhance pest management efforts and lessen the reliance on synthetic chemical solutions (Dassanayake *et al.,* 2021). This suggests that integrating citronella oil into pest management programs can enhance overall control while potentially reducing chemical pesticide use and associated environmental risks. By merging citronella oil with synthetic insecticides, the effectiveness of pest control is heightened through the integration of complementary action modes, which also helps to lower the selection pressure that can lead to resistance in insect pest (Isman, 2006). Overall, the sole citronella oil application (P4) is quite effective in suppressing the population of *A. gossypii*. The capacity to prevent *A. gossypii* population growth was comparable to that of synthetic insecticides (K+). The same pattern also occurred in the by-turn application of synthetic insecticides and citronella oil (P2). At the last observation showed that sole citronella application (P4) could decrease 91% population of *A. gossypii* when it compared with population of *A. gossypii* at K- treatment. When citronella oil was combined with insecticide (P2), there was a significant reduction in the *A. gossypii* population, in contrast to the population observed with only insecticide (K+). This result demonstrates the potential of citronella oil as an effective botanical insecticide. It has been observed that applying treatments weekly is essential, as studies on pests affecting cabbage, mangosteen, and citrus reveal that intervals longer than one week do not significantly reduce pest populations. Therefore, the efficacy of citronella oil is believed to last for no more than one week. Wahba *et al*. (2024) reported that a 10-day application interval for peppermint and eucalyptus essential oils was still effective in controlling *Bemisia tabaci*. Additionally, weather conditions play a significant role in determining the effectiveness of essential oils. Increasing temperature, humidity, and wind speed will increase the effectiveness of peppermint and eucalyptus essential oils in controlling *Bemisia tabaci* pests (Wahba *et al.,* 2024).

Tests of citronella oils toxicity against A. gossypii adult

2. Field test findings suggest that citronella oil

Table 3: Differences in the ability of each pesticide application treatment to suppress the population of *A. gossypii* on chili plants in the field (pest/plant)

Treatment	Observation week ± Standard error (SE)									
	I	II	III	IV	V	VI	VII	VIII	IX	X
P2	31.8 ± 4.2 a	37.3 ± 6.3 b	33.4 ± 5.9 bc	19.8 ± 8.5 b	17.4 ± 1.5 b	1.9 ± 0.2 a	3.1 ± 0.2 a	0.3 ± 0.2 a	1.6 ± 0.3 a	1.2 ± 0.2 a
P4	36.7 ± 7.7 a	22.2 ± 3.3 a	20.2 ± 6.8 a	16.2 ± 10.1 ab	11.8 ± 2.8 a	6.4 ± 1.5 c	3.3 ± 0.2 a	2.7 ± 1.1 b	2.3 ± 0.4 a	2.5 ± 1.0 b
K+	65.4 ±11.6 b	40.2 ± 6.7 b	25.2 ± 3.6 ab	7.6 ± 1.3 a	18.9 ± 1.5 b	3.7 ± 0.3 b	3.9 ± 0.1 b	1.0 ± 0.5 a	2.0 ± 0.2 a	1.9 ± 0.3 b
K-	41.7 ± 8.9 a	38.1 ± 4.5 b	37.7 ± 5.2 c	24.4 ± 13.8 b	24.8 ± 1.3 c	23.5 ± 4.8 d	26.1 ± 1.5 c	24.4 ± 9.8 c	23.5 ± 3.5 b	26.9 ± 5.7 c

Table 4: Average values of the percentage of mortality of *Aphis gossypii* at various concentrations of citronella oil

Treatment	Average value of mortality rate (%)*						
	1 HAA	2 HAA	3 HAA	6 HAA	12 HAA	24 HAA	48 HAA
Control (+)	13.33 a	29.17 b	41.67 c	69.17 c	85.83 c	96.53 d	100.00 d
1 mL/L	4.17 a	7.50 a	13.33 a	19.17 a	24.17 a	31.49 a	38.25 a
2 mL/L	7.50 a	19.17 b	25.83 b	38.33 b	44.17 b	47.81 b	61.84 b
3 mL/L	10.83 a	20.83 b	34.17 bc	42.50 b	53.33 b	60.66 c	89.08 c

*Significant differences are indicated by the numbers in the same column that are followed by different letters according to Tukey's test at a 5% error level. HAA is hours after application and Control + is the abamectin treatment. The data were transformed into $\sqrt{x + 0{,}5}$ data analysis purposes.

could effectively lower the population of A. gossypii. To explore this further, a laboratory experiment was carried out to examine the insecticidal and repellent properties of citronella oil on A. gossypii, with the goal of determining the mechanisms by which the oil reduces this pest's population. The results of the laboratory test showed that citronella oil can kill *A. gossypii* adults. The oil is lethal from 1 mL/L. During the observation period, there is a noticeable increase in the mortality percentage of this pest in relation to the concentration levels. Foliar spraying is the most effective method for applying botanical insecticide, ensuring uniform coverage and direct pest contact to maximize its repellent and insecticidal effects in field conditions (Isman, 2006). However, the toxicity of citronella oil is still lower than the toxicity of synthetic pesticides (K+) (Table 4).

The insecticidal effects of citronella oil on *Aphis gossypii* were most pronounced at a concentration of 3 mL/L, achieving 50% mortality within 12 hours of application. The 2 mL/L treatment showed a comparable effect within the same period, whereas the 1 mL/L concentration required approximately 24 hours to reach the same mortality rate. In contrast to the synthetic pesticide abamectin, which resulted in 50% mortality within only 3 to 6 hours, citronella oil showed significantly lower toxicity. Similar findings were reported by Saleh *et al.* (2023), highlighting that botanical insecticides generally require longer exposure times to reach peak effectiveness. This delayed mortality implies that to achieve effective pest suppression in the field, it may be necessary to apply citronella oil repeatedly, thereby presenting a feasible natural alternative to synthetic insecticides in integrated pest management strategies.

Tests of citronella oils repellence to A. gossypii

The repellence test results demonstrated that adults of *A. gossypii* are repelled by citronella oil. As the concentration of citronella oil rose, its repellency percentage also increased. The comprehensive results of this experiment are displayed in Table 5.

The results of the repellency assay indicated that citronella oil was effective in deterring Aphis gossypii, and its repellent properties became stronger with increased concentration. At a concentration of 3 mL/L, repellency reached 48% within the first hour, highlighting citronella oil's potential as a natural deterrent against aphid infestations. These findings are consistent with the work of Nerio *et al.* (2010), who also observed strong repellent properties of essential oils against agricultural pests. Citronella oil's effectiveness in repelling pests without exterminating them indicates its significant potential in integrated pest management, especially for thwarting the initial invasion of crops. Analysis of variance revealed that

Table 5: Repellence percentage of *Cymbopogon nardus* oil against *A. gossypii*

Treatment	Repellence (%)*		
	1 HAA	2 HAA	3 HAA
1 mL/L	21.22 a	16.44 a	8.77 a
2 mL/L	39.44 b	24.55 ab	12.77 a
3 mL/L	48.00 c	31.77 b	18.60 b

*Significant differences are indicated by the numbers in the same column that are followed by different letters according to Tukey's test at a 5% error level. HAA is hours after application and Control + is the abamectin treatment. The data were transformed into $\sqrt{x + 0{,}5}$ for data analysis purposes.

the highest repellency was observed at 3 mL/L, and this was significantly higher compared to the lower concentrations of 1 and 2 mL/L. No significant difference was found between the repellency rates at 1 and 2 mL/L within the first 1-2 hours after application. Furthermore, repellency increased gradually from 1 to 3 hours across all treatments.

Environmental impact and sustainability

Citronella oil offers a sustainable alternative to synthetic insecticides, reducing environmental contamination and pesticide resistance. The use of botanical insecticides, characterized by their complex blend of bioactive compounds, should be complemented with other pest control methods and ongoing resistance monitoring to effectively manage the potential for resistance development over time (Chaturvedi, 2007). Unlike chemical pesticides, citronella oil biodegrades rapidly, minimizing its persistence in soil and water. Additionally, botanical pesticides are recognized for their reduced effects on non-target species, including beneficial insects such as pollinators and natural predators (Jankowska *et al.,* 2017). This makes citronella oil an environmentally friendly option for integrated pest management programsAdditional studies are necessary to assess the long-term impacts of this approach on agroecosystems and to determine how well it integrates with other biological control strategies. The efficacy of citronella oil in controlling *Aphis gossypii* is likely influenced by environmental conditions, with factors such as temperature, humidity, and rainfall affecting its volatility and degradation rate; therefore, seasonal and multi-location trials are recommended to optimize its use (Cloyd *et al.,* 2009). In addition to analyzing the management of *A. gossypii*, it is essential to consider the possible effects of citronella oil on beneficial insects like pollinators and natural predators. It is recommended that subsequent studies consistently monitor these non-target species (Nerio *et al.,* 2010). Citronella oil provides eco-friendly repellent and insecticidal effects, rapid biodegradation, and minimal non-target impact, though its short residual activity requires frequent applications, which is offset by its environmental benefits (Isman, 2006). Citronella oil is deemed safe owing to its natural formulation and swift degradation; however, its extensive use must align with regulatory requirements and be subject to rigorous safety evaluations (Pathak *et al.,* 2022).

Advanced considerations for future research

This study is to determine the potential of citronella oil as a control agent for *A. gossypii.* While this study confirms the efficacy of citronella oil in controlling *A. gossypii*, additional research is necessary to optimize application frequency, dosage, and formulation for enhanced effectiveness. Investigations into the durability of its action, the likelihood of developing resistance, its effectiveness relative to other botanical pesticides, and its effects on other organisms, especially those that are beneficial, may reveal synergistic relationships between citronella oil and other botanical extracts, paving the way for more powerful formulations. Furthermore, economic feasibility, multi-location trials across different climatic conditions would provide insights into citronella oil's adaptability and broader agricultural applicability. Several obstacles hinder the large-scale adoption of citronella oil, including the stability of its formulations, the need for regular applications, and higher initial expenses. These factors highlight the need for further economic and logistical analysis to determine its practical feasibility (Lengai *et al.,* 2020). Moreover, the field observations suggest that citronella oil applications do not adversely affect chili plant growth or fruit quality, and may enhance yield by reducing pest-induced damage, although further comparative productivity analysis is warranted (Istianto and Emilda, 2021).

CONCLUSION

The findings of this study highlight the significant potential of citronella oil as an effective, environmentally sustainable solution for managing *Aphis gossypii* infestations in agricultural settings, particularly in chili cultivation. The oil exhibited both insecticidal and repellent characteristics, successfully decreasing aphid populations by repelling and poisoning pests, ultimately resulting in their mortality. This study adds to the growing body of evidence supporting the efficacy of citronella oil in pest management, reinforcing its potential as an alternative to synthetic insecticides. Citronella oil's ability to repel and kill insects is linked to its bioactive substances, such as citronellal, citronellol, geranyl acetate, and limonene, which have been proven to disrupt the respiratory processes of insects. These natural compounds offer a promising alternative to chemical insecticides by providing an eco-friendly solution with minimal adverse effects on the environment. Research has previously pointed out that botanical pesticides, including citronella oil, offer the advantage of being less harmful to non-target species, such as pollinators and predatory insects, which are crucial for preserving ecological equilibrium. This characteristic distinguishes citronella oil from synthetic pesticides, which are known to have a negative impact on beneficial species, thus making citronella oil a more sustainable option for integrated pest management (IPM). The study also found that, while citronella oil was successful in lowering aphid numbers, its effects were slower in comparison to those of synthetic insecticides. This finding underscores the need for repeated applications of botanical treatments to achieve the same level of control as chemical options. However, the long-term benefits of using citronella oil, including its environmental safety and the reduced risk of resistance development, make it an attractive alternative. Utilizing citronella oil as part of pest management strategies, particularly in conjunction with synthetic insecticides in a rotational manner, can effectively delay resistance and enhance the sustainability of pest control practices. The use of citronella oil in pest management aligns with global initiatives to promote sustainable agricultural practices. Citronella oil contributes to reducing environmental pollution and promoting biodiversity by decreasing the dependence on synthetic pesticides. Additionally, its biodegradability ensures a lower ecological impact compared to persistent chemical pesticides. These elements establish citronella oil as an essential resource in sustainable agriculture, providing efficient pest management while also promoting ecological conservation. This study provides compelling evidence for the use of citronella oil as a botanical pesticide that not only reduces dependence on chemical insecticides but also offers a more sustainable and environmentally friendly approach to pest management. Its efficacy in controlling *Aphis gossypii* infestations, combined with its minimal impact on non-target organisms, makes citronella oil a valuable addition to integrated pest management strategies. As studies delve deeper into its capabilities, citronella oil has the potential to become a key component in advancing sustainable pest management practices within the agricultural sector.

AUTHOR CONTRIBUTIONS

M. Istianto performed the literature review, conceptualized the central research idea, and designed the study, conducted the experiment, interpretation of results, and manuscript preparation. K.D. Sutanto Performed the literature review, interpreted the data, manuscript preparation and helped in improvement of the manuscript. S. Ikawati performed the literature review, conceptualized the central research idea, designed the study, and analyzed and interpreted the data. R.C. Wicaksono performed the literature review, conceptualized the central research idea, designed the study, data collection and analyzed and interpreted the data, draft manuscript preparation. U. Triasih Performed data collection and analysis and helped in improvement of the manuscript. O. Endarto Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. Affandi Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. Handoko Performed data collection and analysis and helped in improvement of the manuscript. S. Widyaningsih Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. S. Agustini Performed data collection and analysis and helped in improvement of the manuscript. M.E. Dwiastuti Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. L. Mufidah Performed data collection and analysis and helped in improvement of the manuscript. S. Wuryantini Performed data collection and analysis,

interpretation of results, and helped in improvement of the manuscript. I. Nurjanani Performed data collection and analysis and helped in improvement of the manuscript. Yustina Performed data collection and analysis and helped in improvement of the manuscript. D. Setyorini Performed data collection and analysis, interpretation of results, and helped in improvement of the manuscript. D.W. Utami Performed interpretation of results and helped in improvement of the manuscript.

ACKNOWLEDGEMENT

Sincere gratitude goes out to Eva Aprillia Cita Puspitasari, undergraduate student of Plant Protection Agriculture Faculty Brawijaya University, and Sumari, the leader of the farmer group who assisted in conducting this study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the articles Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the articles Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHERS NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
µm	Micrometer
µL	Microliter
a	Number of dead *Aphis gossypii*
A. gossypii	*Aphis gossypii*
ANOVA	Analysis of Variance
b	Number of *A. gossypii* in the treatment
B. tabaci	*Bemisia tabaci*
BPS	Badan Pusat Statistik
C	Quantity of insects in the control
Cm	Centimeter
CMV	Cucumber Mosaic Virus
Conc.	Concentration
E	East
Eq.	Equation
GC–MS	Gas Chromatography–Mass Spectrometry
g/L	Grams per liter
HAA	Hours After Application
ha	Hectare
h	Hours
IPM	Integrated Pest Management
K+	Synthetic insecticide treatment (abamectin)
K-	Untreated control
L	Liter
masl	Meters above sea level
m/z	Mass-to-charge ratio
ml	Milliliter
mL/L	Milliliter per liter
m	Meters
mm^3	Cubic meter
P2	Rotation treatment between citronella oil and synthetic insecticides
P4	Sole application of citronella oil
PVY	Potato Virus Y
Po	Mortality percentage
RBD	Randomized Block Design
R.I.	Repellence index
SE	Standard error
S	South
T	Quantity of insects in the treatment

REFERENCES

Abbott, W.S., (1925). A method of computing the effectiveness of an insecticide. J. Econ. Entomol., 18 (2): 265-267 **(3 pages).**

Agarwal, M.; Verma, A., (2021). Modern technologies for pest control: A review. In book: Biotechnology in Mining and Metallurgical Industry Publisher: IntechOpen Limited, London. 263-268 **(6 Pages)**.

Angelica, P.; Martínez, L.C.; da Silva Rolim, G.; Coelho, R.P.; Santos, M.H.; de Souza Tavares, W.; Serrão, J.E., (2020). Insecticidal and repellent activities of *Cymbopogon citratus* (Poaceae) essential oil and its terpenoids (citral and geranyl acetate) against *Ulomoides dermestoides*, Crop Prot., 137 **(8 Pages).**

BPS, (2023). Luas Panen Tanaman Sayuran Cabai Besar, Cabai Rawit, Cabai Keriting Menurut Kabupaten/Kota dan Jenis Tanaman di Provinsi Jawa Timur (ha), 2021 dan 2022 **(3 Pages).**

Cansian, R. L.; Staudt, A.; Bernardi, J.L.; Puton, B.M.S.; Oliveira, D.; De Oliveira, J.V.; Gomes, A.C.C; Andrade, B.C.O.P.; Leal, I.C.R.; Simas, N.K.; Zeni, J.; Jungues, A.; Dallago, R.M.; Backes, G.T.; Paroul, N., (2021). Toxicity and larvicidal activity on *Aedes aegypti* of citronella essential oil submitted to enzymatic esterification. Braz. J. Biol. 83: e244647 **(5 Pages).**

Chaturvedi, I., (2007). Status of insecticide resistance in the cotton bollworm, *Helicoverpa armigera* (Hubner). J. Central Euro. Agric., 8(2): 171-182 **(12 pages)**.

Chaudhari, A.K.; Singh, V.K.; Kedia, A.; Das, S.; Dubey, N.K., (2021). Essential oils and their bioactive compounds as eco-friendly novel green pesticides for management of storage insect pests: Prospects and retrospects. Environ. Sci. Pol. Res., 28: 18918-18940 **(23 pages)**.

Cloyd, R A.; Galle, C.L.; Keith, S.R.; Kalscheur, N.A.; Kemp, K.E., (2009). Effect of commercially available plant-derived essential oil products on arthropod pests. Journal of Economic Entomology, 102(4): 1567-1579 **(13 pages)**.

Cocuzza, G. (2024). *Aphis gossypii* (cotton aphid). Pest, natural enemy, invasive species, vector of plant pest (CABI Compendium). 1-39 **(39 pages).**

Dassanayake, M.K.; Chong, C.H.; Khoo, T.J.; Figiel, A.; Szumny, A.; Choo, C.M., (2021). Synergistic field crop pest management properties of plant-derived essential oils in combination with synthetic pesticides and bioactive molecules: A rev. Foods. 13(12): 1874 **(19 pages)**.

Jamaluddin, F.; Nurariaty, A.; Amin, N., (2020). The fluctuation of fruit fly attack (*Bactrocera spp*.) in a polycultural system of chili and watermelon crops. In IOP Conference Series: Earth Environ. Sci., 486(1): 012146 **(8 Pages).**

Fouda, M.A.; Al-Daly, A.G.; Mosallam, A.M.Z.; El-Abbassi, T.S.; El-Maaboud, A.S.A.; El-Zouk, A.A., (2017). Evaluation of certain olfactory compounds and natural oils as attractants or repellents for fruit flies in Egypt. Int. J. Adv. Res. Biol. Sci., 4(8): 1–8 **(8 Pages).**

Gharsan, F.N.; Kamel, W.M.; Alghamdi, T.S.; Alghamdi, A.A.; Althagafi, A.O.; Aljassim, F.J.; Al-Ghamdi, S.N., (2022). Toxicity of citronella essential oil and its nanoemulsion against the sawtoothed grain beetle *Oryzaephilus surinamensis* (Coleoptera: Silvanidae). Ind. Crop Prod., 184: 115024 **(7 Pages).**

Gonzaga, K.S.; de Brito, C.H.; Salustino, A.D.S.; de Souza, M.Í.; Santos, J.P.D.O.; Sousa, F.D.A.D.M., (2023). Repellent activity of essential oils against mediterranean fly and their effects on postharvest quality in Paluma guava. Rev. Caatinga. 36(2): 280-290 **(11 Pages).**

Hidayati, N.N.; Yuliani; Kuswanti, N., (2013). Pengaruh Ekstrak Daun Suren dan Daun Mahoni terhadap Mortalitas dan Aktivitas Makan Ulat Daun (*Plutella xylostella*) pada Tanaman Kubis, Lentera Bio., 2(1): 95–99 **(5 Pages)**.

Ikawati, S.; Dhuha, M.; Himawan, T., (2017). Bioactivity of *Citrus hystrix* D.C. Leaf Extract against Cigarette Beetle *Lasioderma serricorne* (F.). J. Trop. Life Sci., 7(3): 189–196 **(8 Pages)**.

Isman, M.B., (2006). Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Ann. Rev. entomol., 51(1): 45-66 **(12 pages).**

Istianto, M.; Emilda, D., (2021). The potency of Citronella oil and Clove oil for pest and disease control in tropical fruit plants. IOP Conference Series: Earth Environ. Sci., 739(1): 012064 **(8 Pages)**.

Jamaluddin, F.; Nurariaty, A.; Amin, N., (2020). The fluctuation of fruit fly attack (*Bactrocera spp.*) in a polycultural system of chili and watermelon crops. IOP Conference Series: Earth Environ. Sci., 486(1): 012146 **(8 Pages)**.

Lahlali, R.; El Hamss, H.; Mediouni-Ben Jemâa, J.; Barka, E.A., (2022). The use of plant extracts and essential oils as biopesticides. Front. Agron., 4: 921965 **(4 pages)**.

Lee, M.Y., (2018). Essential Oils as Repellents against Arthropods, BioMed Res. Int., 2018(1): 6860271 **(9 pages)**.

Lengai, G.M.; Muthomi, J. W.; Mbega, E.R., (2020). Phytochemical activity and role of botanical pesticides in pest management for sustainable agricultural crop production. Sci. Afr., 7: e00239 **(13 pages).**

Matsumura, F., (2012). Toxicology of insecticides. SSBM. 1-10 **(10 pages).**

Milonas, P.G.; Anastasaki, E.; Psoma, A.; Partsinevelos, G.; Fragkopoulos, G.N.; Kektsidou, O.; Kapranas, A., (2023). Plant viruses induce plant volatiles that are detected by aphid parasitoids. Sci. Rep., 13(1): 8721 **(12 Pages).**

Nerio, L.S.; Olivero-Verbel, J.; Stashenko, E., (2010). Repellent activity of essential oils: A review, Bioresour. Technol., 101(1): 372–378 **(7 Pages)**.

Nindatu, M.; Moniharapon, D.; Latuputty, S., (2016). Efektifitas Ekstrak Cabai Merah (*Capsicum annum* L) Terhadap Mortalitas Kutu Daun (*Aphis gossypli*) Pada Tanaman Cabai, Agrologia, 5(1): 288745 **(5 pages).**

Özkara, A.; Akyıl, D.; Konuk, M., (2016). Pesticides, environmental pollution, and health. In Environmental health risk-hazardous factors to living species. Environmental health risk-hazardous factors to living species. 4(1): 1-27 **(26 Pages).**

Pascual-Villalobos, M.J.; Robledo, A., (1998). Screening for anti-insect activity in Mediterranean plants. Ind. Crop Prod., 8(3): 183–194 **(12 Pages)**.

Pathak, V.M.; Verma, V.K.; Rawat, B.S.; Kaur, B.; Babu, N.; Sharma, A.; Dewali, S.; Yadav, M.; Kumari, R.; Singh, S.; Mohapatra, A.; Pandey, V.; Rana, N.; Cunill, J.M., (2022). Current status of pesticide effects on environment, human health and its eco-friendly management as bioremediation: A comprehensive review. Front. Microbial., 13: 962619 **(29 Pages).**

Popescu, I.E.; Gostin, I.N.; Blidar, C.F., (2024). An overview of the mechanisms of action and administration technologies of the essential oils used as green insecticides. Agric. Eng., 6(2): 1195-1217 **(23 pages)**.

Rattan, R.S., (2010). Mechanism of action of insecticidal secondary metabolites of plant origin. Crop prot., 29(9): 913-920 **(8 pages).**

Thangjam, R.; Kadam, V.; Nath, P.D.; Borah, R. K., (2023). Insect Vectors Associated with Viral Diseases of King Chilli (*Capsicum chinense* Jacq.) in North East India. Indian J. Entomol., 85(3): 672–675 **(4 Pages)**.

Saad, K.A.; Roff, M.M.; Idris, A.B., (2017). Toxic, repellent, and deterrent effects of citronella essential oil on *Bemisia tabaci* (Hemiptera: Aleyrodidae) on Chili plants. J. Entomol. Sci., 52(2): 119–130 **(12 Pages)**.

Saleh, S.; Pasaru, F.; Toana, M.H.; Syair, M.; Wangi, A.S., (2023). Antifeedant and toxicity effect of citronella essential oil against *Spodoptera frugiperda* JE Smith larvae. IOP Conference Series: Earth Environ. Sci., 1253(1): 012006 **(7 Pages).**

Sarwar, M., Salman, M. (2015). Insecticides resistance in insect pests or vectors and development of novel strategies to combat its evolution. Int. J. Bioinformat. Biomed. Eng., 1(3): 344-351 **(8 pages).**

Siddiqui, J.A.; Fan, R.; Naz, H.; Bamisile, B.S.; Hafeez, M.; Ghani, M.I.; Wei, Y.; Xu, Y.; Chen, X., (2023). Insights into insecticide-resistance mechanisms in invasive species: Challenges and control strategies. Front. Physiol., 13: 1112278 **(18 Pages)**.

Siviter, S.; Muth, F., (2020). Do novel insecticides pose a threat to beneficial insects? Proceeding R. Soc. B., 287(1935): 20201265 **(9 Pages).**

Wahba, T.F.; Abd-Elatef, E.A.; Wahba, M.N., (2024). Field effectiveness of some essential oil emulsions against the whitefly *Bemisia tabaci* (GENN.) that infest potato plants in Egypt. J. Plant Dis. Protect., 131(5): 1451-1463 **(13 pages)**.

Wicaksono, R.C.; Istianto, M.; Setiawati, W.; Tarigan, R.; Triasih, U.; Endarto, O.; Setyorini, D., (2023). The effectiveness of citronella oil to control main pest on cabbage *Plutella xylostella* in the field. J. Entomol. Acarol. Res., 55(1): 11751 **(7 Pages).**

Wiratno, Sutanto, K.D.; Nurawan, A.; Taufik, I.; Surdianto, Y.; Sutrisna, N.; Rizal, M.; Karmawati, E; Siswanto; Soetopo, D.; Trisawa, I.M.; Rismayani; Rahardjo, I.B., (2025). Eco-friendly botanical insecticides to control brown leafhoppers and their effects on the predators and aquatic environment. Global J. Environ. Sci. Manage., 11(1): 113-128 **(16 pages).**

AUTHOR (S) BIOSKETCHES

Istianto, M., Ph.D., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *mizu_istianto@yahoo.com*
▪ ORCID: 0000-0001-6345-7743
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 15829770800
▪ Homepage: https://hpt.faperta.ugm.ac.id/

Sutanto, K.D., Ph.D., Postdoctoral fellow, Research Center for Horticulture, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *koko006@brin.go.id*
▪ ORCID: 0000-0002-3605-4954
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 55980814800
▪ Homepage: http://ksu.edu.sa/index.php/en/home

Ikawati, S., Ph.D., Senior researcher, Department of Plant Pests and Diseases, Faculty of Agriculture, Brawijaya University. Jl. Veteran, Malang 65145, East Java, Indonesia
▪ Email: *silviikawati@ub.ac.id*
▪ ORCID: 0000-0001-8731-2055
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57208009842
▪ Homepage: https://fp.ub.ac.id/entomologi-pertanian/profil-ps-entomologi/

Wicaksono, R.C. M.Sc., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *rudicahyo@gmail.com*
▪ ORCID: 0000-0002-2515-0879
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57220221176
▪ Homepage: https://fp.ub.ac.id/entomologi-pertanian/profil-ps-entomologi/

Widyaningsih, S., Ph.D., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *sri.wiwied74@gmail.com*
▪ ORCID: 0000-0002-5250-9082
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 58319131800
▪ Homepage: https://hpt.faperta.ugm.ac.id/

Dwiastuti, M.E., M.Sc., Senior Researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *mutiaed@gmail.com*
▪ ORCID: 0000-0002-1567-5049
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 56048976500
▪ Homepage: https://hpt.faperta.ugm.ac.id/pascasarjana/program-studi-s2-minat-studi-s3-fitopatologi/

Triasih, U., M.Sc., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *unun001@brin.go.id*
▪ ORCID: 0000-0003-0289-395X
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57224203878
▪ Homepage: https://fp.ub.ac.id/patologi-tumbuhan/profil-ps-patologi/

Endarto, O., M.Sc., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *endarto11@gmail.com*
▪ ORCID: 0000-0001-9927-6143
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57216755641
▪ Homepage: https://ipb.ac.id/page/plantprotection2/

Affandi, Ph.D., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *affandiaffandi1970@gmail.com*
▪ ORCID: 0000-0003-1132-5831
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 55981822000
▪ Homepage: https://uplb.edu.ph

AUTHOR (S) BIOSKETCHES

Handoko, M.Sc., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *ndokondoro@gmail.com*
▪ ORCID: 0000-0002-9377-275x
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 58306859200
▪ Homepage: https://uplb.edu.ph

Yustina, I. M.Sc**,** Senior researcher, Directorate for Scientific Collection Management, National Research and Innovation Agency Jl. M.H. Thamrin No. 8 Jakarta Pusat,10340 Indonesia.
▪ Email: *itay001@brin.go.id*
▪ ORCID: 0000-0002-0725-7226
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 5798963100
▪ Homepage: https://tp.ugm.ac.id/id/

Mufidah, L., M.Sc., Senior researcher, Research Center for Behavioral and Circular Economics, National Research and Innovation Agency. PPID Building, Jl. Jend. Gatot Subroto No.10, Jakarta Selatan, 12710.
▪ Email: *lyli001@brin.go.id*
▪ ORCID: 0000-0002-4655-9550
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57216347469
▪ Homepage: https://tp.ugm.ac.id/id/

Wuryantini, S., M.Sc., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: susi014@brin.go.id
▪ ORCID: 0000-0002-7585-7987
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57216315224
▪ Homepage: https://fp.ub.ac.id/entomologi-pertanian/profil-ps-entomologi/

Nurjanani, M.Sc., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *nurjanani_nani@yahoo.com*
▪ ORCID: 0009-0001-6581-9207
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57217525659
▪ Homepage: https://ptn.ipb.ac.id/

Agustini, S. M.Sc., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *sri8agustini31@gmail.com*
▪ ORCID: 0000-0003-0273-2574
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 5587273390
▪ Homepage: http://upr.ac.id

Setyorini, D., Ph.D., Senior researcher, Research Center for Estate Crops, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *dwis015@brin.go.id*
▪ ORCID: 0000-0002-3808-5578
▪ Web of Science Researcher ID: rinibptpjatim@gmail.com
▪ Scopus Author ID: 55753332700
▪ Homepage: https://fp.ub.ac.id/ilmu-pertanian/

Utami, D.W., Ph.D., Senior researcher, Research Center for Horticulture, National Research and Innovation Agency Jl. Raya Jakarta-Bogor KM 46, Cibinong, Indonesia.
▪ Email: *dwin011@brin.go.id*
▪ ORCID: 0000-0002-5873-0570
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 36821685400
▪ Homepage: https://www.ipb.ac.id/page/agrohort2/

HOW TO CITE THIS ARTICLE

Istianto, M.; Sutanto, K.D.; Ikawati, S.; Wicaksono, R.C.; Widyaningsih, S.; Dwiastuti, M.E.; Triasih, U.; Endarto, O.; Affandi; Handoko; Yustina, I.; Mufidah, L.; Wuryantini, S.; Nurjanani; Agustini, S.; Setyorini, D.; Utami, D.W, (2025). Sustainable pest management with citronella oil for eco-friendly control of Aphis gossypii in chili plants. Global J. Environ. Sci. Manage.., 11(2): 733-746.

DOI: 10.22034/gjesm.2025.02.20

URL: https://www.gjesm.net/article_722022.html

Global J. Environ. Sci. Manage. 11(2): 747-770, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

CASE STUDY

Multi-dimensional perspectives on sustainability in domestic waste management

Y. Ismail[1], R. Adji[2], A.D. Santoso[3,*], S. Wahyono[4], M.A. Kholiq[5], T. Handayani[3], S.D.R. Pahri[6], S. Putiamini[5], R.A. Pratama[4], F. Nurfatriani[5], F.L. Sahwan4, F. Suryanto[4], Prasetiyadi[4], R.D. Tilottama[4]

[1] *Study Program of Environmental Engineering, Faculty of Engineering, President University, Indonesia*

[2] *Study Program of Agribusiness, Faculty of Business, President University, Indonesia*

[3] *Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia*

[4] *Research Center for Environmental and Clean Technology, National Research and Innovation Agency, Indonesia*

[5] *Directorate of Environment, Maritime, Natural Resources and Nuclear Policy, National Research and Innovation Agency, Indonesia*

[6] *Centre for Research in Development, Social and Environment, Faculty of Social Sciences and Humanities, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia*

ARTICLE INFO

Article History:
Received 15 December 2024
Revised 18 February 2025
Accepted 25 March 2025

Keywords:
Community based waste management
Multidimensional scaling
Social engagement
Waste management sustainability

DOI: 10.22034/gjesm.2025.02.21

ABSTRACT

BACKGROUND AND OBJECTIVES: Sustainable waste management is a critical global challenge, demands a multifaceted approach to evaluate and boost its effectiveness. This study evaluates the sustainability of domestic waste management using a multi-dimensional scaling framework, focusing on five fundamental parameters,
such as environmental, economic, social interactions, technological, and regulatory sustainability. This study aims to pinpoint key leverage points for focused enhancements, promoting sustained resilience and efficiency within the system.
METHODS: A mixed-method approach was employed, combining literature reviews, research journal analysis, and initial data collection. Standardized surveys and focus group discussions were performed with stakeholders, including plant operators, managers, and experts. The rapid appraisal tool for waste management was used to assess thirty-three sustainability attributes, with responses measured using a Likert scale. The results were classified into four sustainability levels: unsustainable, less sustainable, fairly sustainable, and sustainable, which facilitated a structured analysis of the system's performance.
FINDINGS: The analysis indicates moderate sustainability across all dimensions, with economic sustainability scoring the highest at 55.27 percent signifying its role as the system's backbone. Nonetheless, there is a significant need for advancement in the areas of financial management and leadership. Technological sustainability followed at 54.44 percent, reflecting incremental advancements but underscoring the need for innovative waste treatment technologies. With a score of 52.12 percent, social sustainability reflects significant community engagement but also uncovers shortcomings in environmental education. The environmental dimension scored 47.1 percent, with leadership and inter-institutional cooperation emerging as under-utilized yet crucial factors. Ranking at a mere 45.1 percent, institutional sustainability was the lowest, indicating an urgent demand for effective governance structures and enhanced inter-agency collaboration.
CONCLUSION: Strengthening institutional frameworks through leadership development and formalizing inter-agency partnerships is essential for improving sustainability. Economic resilience can be fostered by incentivizing community-based waste management through grants and subsidies. Additionally, targeted public education and community engagement initiatives can bridge social sustainability gaps. The system exhibits a fair amount of progress; however, it is vital to undertake strategic actions to secure long-term sustainability and ensure it aligns with global environmental objectives.

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
66	9	5

*Corresponding Author:
Email: *arif.dwi.santoso@brin.go.id*
Phone: +62852 8611 2334
ORCID: 0000-0003-3595-9265

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

The global waste crisis has grown into one of the most severe environmental challenges, exacerbated by rapid population growth, urbanization, and increasing consumption patterns (Ferronato and Torretta, 2019). With the ongoing rise in waste generation, poor waste management practices are exacerbating serious environmental issues, including land and water pollution, biodiversity loss, and greenhouse gas (GHG) emissions (Dinis *et al*., 2022). Without effective waste management strategies, the accumulation of waste poses serious threats to public health and the sustainability of ecosystems (Godfrey *et al*., 2020). The issue of waste generation is a pressing environmental concern on a global scale, with annual solid waste production exceeding 2.24 billion tons, and over a third of this waste is not managed appropriately (Kaza *et al*., 2018). Developed nations such as Germany, Sweden, Japan, South Korea, and Singapore have achieved high recycling rates through integrated waste management systems and strict waste separation policies. Conversely, Indonesia faces ongoing challenges with inefficient waste management, predominantly utilizing landfills for disposal and lacking community-oriented practices for waste segregation (Lerpiniere *et al*., 2025). Limited infrastructure and insufficient funding remain key barriers to develop a sustainable waste management system. To overcome these obstacles, it is essential to implement policy changes, enhance waste separation techniques, and invest in recycling facilities to ensure sustainable practices in the long run. Sustainable waste management is essential for balancing human activities with environmental preservation. It not only mitigates pollution but also supports resource efficiency by promoting recycling, composting, and waste-to-energy (WTE) initiatives (Ahmad *et al*., 2015). A well-structured waste management system reduces landfill dependence, minimizes environmental hazards, and enhances economic opportunities through circular economy principles (Kurniawan *et al*., 2021). Sustainability indicators are crucial for assessing the effectiveness of these systems, as they measure waste management efficiency, evaluate environmental impacts, and inform policy development (Mulyatna *et al*., 2021). These indicators provide insights into key factors such as waste collection rates, recycling efficiency, and GHG emissions, helping policymakers make evidence-based decisions for long-term sustainability (Dinis *et al*., 2022). With the ongoing rise of urbanization, current waste management systems are under increasing strain to adjust to the growing volumes of waste and changing patterns of consumption. Identifying and implementing sustainable waste management strategies is critical to address the mitigating of global waste crisis while fostering environmental resilience and socio economic stability (Ferronato and Torretta, 2019). A comprehensive approach that integrates technological innovation, public participation, and strong policy frameworks is crucial for addressing waste-related challenges and ensuring a sustainable future. Indonesia, the largest archipelagic nation in Southeast Asia with a population of 275 million, generates over 65 million tons of municipal solid waste (MSW) annually, ranking among the world's largest waste producers (Hadinata *et al*., 2018; Kurniawan *et al*., 2021; World Bank, 2024). Only 7 percent (%) of Indonesia's total municipal solid waste (MSW) is recycled, with the remainder primarily ending up in open dumps sites or landfills (Jambeck *et al*., 2015; Khair *et al*., 2019). Inadequate sanitation at certain sites creates serious threats to environmental integrity and public health, causing pollution in water, soil, and air, and enabling the increase of disease vectors (Matee and Senzia, 2023). The environmental consequences of Indonesia's waste management inefficiencies are significant. Methane emissions from decomposing waste exceed three million tons per year, representing 16% of global methane emissions (Lando *et al*., 2021). Methane is a prominent greenhouse gas that contributes to climate change, reinforcing the urgent requirement for better waste management solutions (Eric, 2024; Pandey *et al*., 2015). Inadequate waste management practices, such as open dumping, inefficient landfills, and poor waste segregation, have severe long-term environmental impacts on soil health and biodiversity. Unregulated landfills contribute to soil contamination through leachate infiltration, reduce fertility and disrupt microbial communities, while plastic pollution and hazardous waste accumulation threaten ecosystems (Chen *et al*., 2025). Each year, Indonesia generates over three million tons of methane emissions from decaying waste, which plays a major role in exacerbating climate change (Sumarlin *et al*., 2023; Lando *et al*., 2021). To mitigate these effects, policy interventions

such as stricter landfill regulations, mandatory waste segregation, and Extended Producer Responsibility (EPR) can enhance waste recovery and recycling efforts (Liu *et al*., 2025). Enhancing enforcement strategies, advocating for WTE innovations, and expanding community-driven waste management programs, it can be effectively lessening environmental degradation and enhance sustainability. Regardless these challenges, significant potential exists for improvement Indonesia's waste management system. Waste bank programs that encourage community-based recycling have demonstrated potential in decreasing household waste (Khair *et al*., 2019). These programs, notably in metropolitan regions where waste sorting is more achievable, highlight the nation's ability to advance its recycling initiatives. Rimantho *et al*. (2022) highlights the recycling potential of domestic and commercial waste streams, specifically focusing on plastics and organic waste, which are identified as the most valuable materials for recycling. Ferdinan *et al*. (2022) created an index to analyze the efficiency of waste management operations by examining important characteristics such as waste elimination, recycling rates, and community engagement. This index serves as a quantitative tool for analyzing and refining waste management strategies. To confront the challenges of waste management, the Indonesian government has introduced various legislative and regulatory initiatives. Law Number 18 of 2008 on trash Management and the National Policy and Strategy for Waste Management (JAKSTRANAS) aim to achieve a 30% decrease in trash and a 70% increase in recycling by 2025 (Owusu-Acheampong *et al*., 2024). These efforts encounter substantial obstacles, such as insufficient infrastructure, limited public awareness, and irregular policy enforcement (Fariz *et al*., 2024). Financing issues and a lack of inter-agency collaboration pose major obstacles to the successful implementation of waste management programs. The absence of strong institutional support and active public involvement makes it challenging to reach these policy objectives (Khair *et al*., 2019 ; Kurniawan *et al*., 2021). Agamuthu and Babel (2023) contend that a circular economy approach, which optimizes resource recovery and reduces waste generation, may provide a more sustainable solution to Indonesia's waste management issues. Community-based disposal management solutions have arisen as a feasible solution to the Indonesian waste challenge, alongside government initiatives (Muktiningsih *et al*., 2023; Pratama *et al*., 2023). Rachman *et al*. (2016) present a model that combines composting and plastic recycling, specifically targeting rural and semi-urban regions with elevated local engagement. These models have demonstrated success in decreasing waste and improving sustainability within local communities, particularly in areas where governmental support is often insufficient. Integrating community-based models with national policies may enable Indonesia to construct a more sustainable and effective disposal management system that caters to the needs of both urban and rural areas (Ismiraj *et al*., 2023). This research was applied in the districts of Banyumas to analyze the business processes of domestic waste management in both areas. From 2018 to 2022, these regions made notable advancements in waste management, emerging as a leading example for other areas and nearby countries due to their efficient and sustainable approaches (Salam *et al*., 2021). During this period, the system efficiently processed domestic waste into three valuable co-products: recyclable materials that were sent to recycling industries, organic waste pulp used for feeding black soldier fly (maggot) larvae, and non-recyclable plastics converted into refuse derived fuel (RDF). However, in the past two years, the performance of waste management in both areas has declined, leading to waste accumulation at a reuse-reduce-recycle waste processing site (TPS3R) facilities and other storage sites (Chairani *et al*., 2023). The purpose of this study is to pinpoint the essential aspects of the waste management process that have contributed to this downturn, with the intention of revitalizing the system's sustainability to its prior achievements. While various tools and methods have been employed to assess sustainability, the integration of multi-dimensional scaling (MDS) in Indonesia's waste management system represents a novel approach. MDS allows for the evaluation of multiple dimensions environmental, social, economy, and technological providing a complete and quantitative representation of complex relationships within waste management systems. By adopting a transdisciplinary framework that encompasses environmental, economic, social, and technological aspects, this research delivers an all-encompassing analysis of the sustainability of Indonesia's waste

management system. The use of MDS to develop a sustainability index highlights key factors and critical drivers influencing waste management performance, providing policymakers with valuable insights for future strategies. This novel framework addresses the complexities of human-environment dynamics and offers a robust basis for decision-making aimed at achieving long-term sustainability. To determine the sustainability of Indonesia's waste management system, it is essential to adopt a thorough approach that integrates environmental, social, economic, and technological aspects. MDS is a useful way to assess the sustainability of various systems (Rachman *et al*., 2016). MDS offers a numerical representation of complex relationships, facilitating the assessment of similarities between groups, particularly in the context of waste management practices (Nieves and Delgado Ramos, 2023). The choice of MDS stemmed from its ability to flexibly analyze complex sustainability factors while considering the viewpoints of both experts and participants. Unlike life cycle assessment (LCA), which focuses mainly on environmental impact, or Analytical Hierarchy Process (AHP) and Fuzzy Logic models, which rely on rigid criteria, MDS provides a more adaptive and holistic assessment of waste management sustainability. MDS, initially utilized in fisheries policies, has been subsequently submitted in various agricultural comodities, such as algae biomass production (Santoso *et al*., 2023), duck farming (Bakrie *et al*., 2023), chocolate (Fairuzia *et al*., 2020), compost (Santoso *et al*., 2023a), beef (Rohaeni *et al*., 2024), buffalo (Rohaeni *et al*., 2023) dairy (Lovarelli *et al*., 2020), shrimp (Sivaraman *et al*., 2019), rice (Rachman *et al*., 2022), coconut sugar (Handayani *et al*., 2025), coffee (Yusuf *et al*., 2022), black soldier fly (Santoso *et al*., 2023b), integrated farming (Widjaja *et al*., 2023), and sago (Allaily *et al*., 2024). An index may provide a foundation for evaluating the effectiveness of Indonesia's waste disposal strategies, influencing future policy decisions to foster more sustainable outcomes. This study seeks to analyze the sustainability of Indonesia's domestic waste management system utilizing MDS as a framework. This research seeks to: 1) identify critical factors influencing waste management sustainability, 2) develop a sustainability index for Indonesia's waste sector, and 3) provide policy recommendations for improving waste management efficiency. The present research project was carried out at the Directorate of Environment, Maritime, Natural Resources, and Nuclear Policy, National Research and Innovation Agency, Indonesia in 2024.

MATERIALS AND METHODS

Research materials and procedure

This research concentrated on analysing the sustainability of the waste procedure in Banyumas regency and Purwokerto district, Central Java through a MDS approach. Literature and indexed research journals provided secondary data regarding the elements that support the sustainability of disposal management. The primer data was added to with information from a focus group discussions (FGDs) and the finalization of a structured question sheet covering 33 attributes related to the environmental, economic, social, technological, and institutional features of disposal systems. The selection of respondents was deliberate, focusing on individuals with a minimum of five years of experience who are actively engaged, skilled, and well-informed about waste management system. The respondents including plant operator, plant manager, waste management specialist, and entrepreneurs, were interviewed. The sustainability dimensions of MSW management are deeply interconnected, influencing system effectiveness and long-term viability. Economic considerations are pivotal in fostering investment in waste management systems and technological innovations. Studies reveal that financial strategies support the implementation of circular economy models and boost resource recovery rates, highlighting the link between economic value scores and successful waste management outcomes (Ferdinan *et al*., 2022). Institutional frameworks provide regulatory support, governance, and financial mechanisms to sustain these investments, particularly through policies that integrate stakeholder participation and optimize processes (Khosravani *et al*., 2023). Technological advancements enhance operational efficiency and environmental protection but require economic feasibility and institutional backing for large-scale adoption, as seen in cases where facility availability directly correlates with waste management outcomes (Ferdinan *et al*., 2022; Khosravani *et al*., 2023). Effective waste segregation and recycling heavily rely on social engagement, which includes public participation and shifts in

behavior. Research demonstrates that the knowledge and perspectives of the community have a direct effect on environmental sustainability (Widyaningsih *et al*., 2022). Strong institutional policies foster social inclusion, particularly in integrating informal waste sectors into formal systems, improving both economic and environmental outcomes (e.g., waste banks mobilizing community participation). A circular economy approach aligns economic growth with environmental benefits by promoting resource recovery and reducing reliance on landfilling (Ferdinan *et al*., 2022). Waste really affects sustainable agricultural processes, and of course this has a big impact on sustainable agricultural businesses. Furthermore, the contributions and correlation of five MSW dimensions toward sustainable MSW management in as shown in Fig 1.

Characteristics of the waste management in the location study

The study was performed in Banyumas district of Central Java Province, Indonesia. Banyumas Regency covers approximately 1,391.15 square kilometers (km^2) with a population estimated at 1,828,573 people at 2023 (Central Bureau of Stastitic, 2023). The glocation of the study area in Banyumas District of Central Java Province is shown in Fig. 2.

Assuming each resident generates an average of 0.32 kilograms (kg) of waste daily, the Regency is projected to produce around 585.14 tons of household waste per day. In Banyumas Regency, the approach to waste management is structured around three primary stages: upstream, midstream, and downstream. The ideal model, as illustrated in the provided image (Fig. 3), was designed to ensure that waste is sorted, processed, and disposed of efficiently, thereby minimizing the burden on final disposal sites (TPA). Nevertheless, the practical execution of this system has run into various operational inefficiencies, mainly caused by limitations in infrastructure and alterations in policy that followed changes in regional governance.

These challenges have disrupted the intended waste management flow, resulting in an increased volume of unprocessed waste reaching landfills. At the upstream level, waste is expected to be sorted at the household level, where organic waste is managed via Sampah online banyumas android-based waste management aplication (SALIMAS), and non-organic waste is handled through JEKNYONG. Waste banks

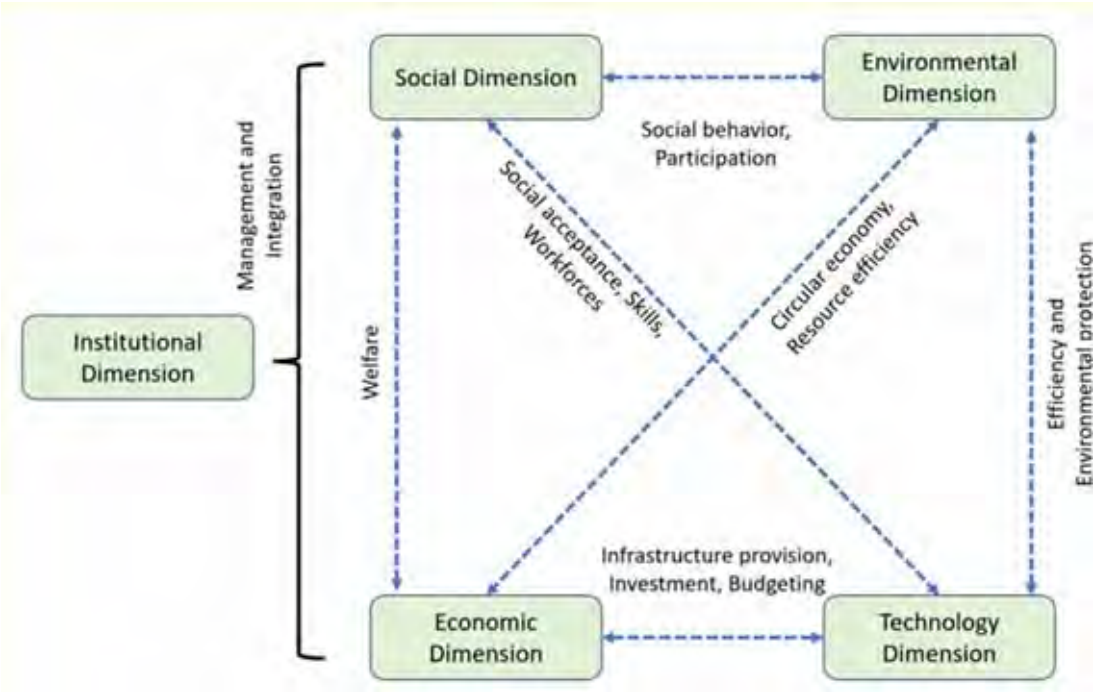


Fig. 1: The cotribution and correlation of five MSW dimensions, modified from (Khosravani *et al*., 2023)



Fig. 2: Geographical location of the study area in Banyumas District of Central Java Province, Indonesia



Fig. 3: Diagram of waste management at Banyumas district

Table 1: Waste management stations (TPSTs) at Banyumas District

No	TPSTs name	Capacity (t/day)	Personnel (person)	Waste generated (t/day)	Household
1	Soka Negara	5	20	5-6	974
2	Kedung Gede	9	25	9	730
3	Sumpiuh	10	31	10	1,008
4	Patik Raja	15	38	15	2,972
5	Karangklesem	8	19	4-5	1,342
6	Mugi Resik	9	15	3	1,681
7	Cilongok*	3	23	2	N/A
8	Bawa Berkah	10	29	8	1,404
9	Rawalo	8	19	2	1,087
10	Tipar Kidul	9	32	12	980
11	Arca Satria	10	4	4	1,010
12	Kamandaka	7	10	2	8,000
13	Migunami	8	15	6	956
14	Sejahtera	6	14	6	1,258
15	Sapu Resik	5	10	5	1,200
16	Cemara	1	4	1	530
17	Brayan	7	18	7	1,000
18	Gempar Jaya	8	12	4	1,160
19	Mandari	5	20	5	1,300

*Newly established

are vital in managing and redistributing recyclable materials that have financial significance. However, many households fail to sort or process their waste properly, and due to inefficiencies in the community self-help groups (KSMs) that are responsible for handling unprocessed waste, large quantities bypass the midstream stage and are sent directly to landfills. This interferes with the structured waste disposal process, compelling landfills to accept waste that ought to have been processed earlier. To support these KSMs, the Banyumas government constructed more than 19 multiple waste management stations (TPSTs) to accommodate unprocessed residual waste (Table 1).

In the midstream phase, TPSTs are responsible for processing waste using a combination of manual, mechanical, thermal, and biological methods. Ideally, employing mechanical processing methods such as shredding, composting, and incineration would substantially decrease the volume before it reaches TPA. However, in practice, technical failures in waste-processing machinery, such as sorting machines, waste incinerators, and shredders, frequently disrupt operations. When incinerators malfunction, residual waste that should have been reduced at this stage is instead transported to landfills, contributing to an increasing volume of unprocessed waste. Similarly, when shredders fail, non-organic waste that should have been repurposed into RDF remains unprocessed, further adding to landfill burden. The downstream phase is designed to manage final disposal through pyrolysis at TPST facilities before waste is sent to TPA. Nevertheless, due to the suboptimal functioning of the upstream and midstream processes, TPAs are encountering an overload of waste materials. Furthermore, the restricted processing capabilities of the TPSTs, coupled with inefficiencies in waste conversion facilities such as extruder and paving block production systems, has resulted in further waste accumulation. Consequently, a significant amount of RDF waste is left unmanaged instead of being converted into construction materials, further aggravating landfill overflow. The failures within the system reveal an urgent need for intervention to streamline waste processing throughout all levels. Ensuring that TPSTs function effectively, maintaining waste-processing infrastructure, and reinforcing household participation in waste sorting are essential for reducing the volume of waste reaching landfills. Furthermore, stronger policy enforcement and government support are needed to sustain a functioning, integrated waste management system in Banyumas. Without these improvements, the region risks continued environmental and operational inefficiencies, undermining the sustainability goals of its waste management framework.

Data analysis

Acquiring secondary data involves the collection of information from waste management guidelines, scholarly articles, and other relevant literature concerning income and the sustainability of waste management system. Primary and secondary data were acquired via FGDs and the submission of a question sheet covering 33 attributes related to environmental, social, economy, technological, and institutional concerns. This study specifically selected respondents who are actively engaged, skilled, and well-informed about waste management systems. FGDs were conducted to review the survey data, and six experts with at least five years of involvement in comprehensive waste management, including plant operators, plant managers, waste management experts, and entrepreneurs, were interviewed. An analysis of waste management sustainability was performed through the MDS approach, leveraging the Rapid Appraisal for waste management analysis tool (Rap-waste). These aspects and traits were defined using a Likert scale-based questionnaire. The Rapfish method, which applies MDS with the ASCAL algorithm, is highly adaptable for sustainability assessments, including waste management. Initially created for the fisheries sector, Rapfish integrates various factors and expert insights across environmental, social, economic, and institutional aspects. This flexibility ensures a comprehensive evaluation of waste-related challenges, making it a suitable tool for assessing waste management sustainability. The MDS implementation in this study followed a structured process: key sustainability attributes were identified, and a questionnaire was developed to capture expert assessments. The collected responses were analyzed using Rapfish software to generate sustainability scores. The findings were subsequently analyzed to evaluate sustainability levels and pinpoint key factors affecting waste management effectiveness. Expert responders answered the question sheet by grading 0 for bad, 1 for average, and 2 for good. The ordination technique used the alternating least squares procedure, which is releted on the Euclidean distance (squared distance) root and is referred to as the ASCAL algorithm. This method determines the ordination or the squared distance (d_{ij}) to squared data (origin = o_{ijk}) in three dimensions (i, j, k), which is then called S-stress. Determination techniques of ordination were depended on Euclidian distance in n-space, using Eq. 1 (Pitcher and Preischot, 2001; Lloyd *et al*., 2022):

$$d = \sqrt{\left(\left|x_1 - x_2\right|^2 + \left|y_1 - y_2\right|^2 + \left|z_1 - x_2\right|^2 + \ldots\right)} \quad (1)$$

Configurations of points in MDS determined by regressing Euclidian distance (d_{ij}) from point i to point j with point of origin (o_{ij}), using Eq. 2 (Lloyd *et al*., 2022):

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (2)$$

The ALSCAL method determine squared distance (squared distance = d_{ijk}) against squared data (point of origin = o_{ijk}), which in three dimensions (i, j, k) is written in a formula called S-stress using Eq. 3 (Pitcher and Preischot, 2001; Lloyd *et al*., 2022):

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (3)$$

Where, the squared distance is Euclidian distance assigned a value, using Eq. 4 (Lloyd *et al*., 2022):

$$d_{ijk} = \sum_{a=1}^{r} w_{ka}\left(x_{ia} - x_{ja}\right)^2 \quad (4)$$

The levels of sustainability performance are divided into 4 levels, resulting in intervals of 0, 25%, 50%, 75%, and 100%. The assessment categories are as follows: 75.01 – 100.00, good category or sustainable, 50.01 – 75.00, adequate category or fairly sustainable, 25.01 – 50.00, less category or less sustainable, and 0.00 – 25.00, poor category or unsustainable, as presented in Table 2.

The values of the leverage factors fall within the range of 2%-8%, indicating a moderate to good impact. If <2%, the factor is considered not influential, while if >8%, the factor is considered dominant (sustainable). Table 3 presents the factors that have an impact and are dominant.

The goal of Monte Carlo analysis is to investigate the chances of errors in establishing indicator score values and to analyze how variations in these scores may result from the differing ways respondents complete the questionnaire. The Monte Carlo simulation was conducted with 25 iterations to

Table 2: Parameter values of the levels of the sustainability performance

No.	Index value	Category	Status
1	0 – 25.0	poor	unsustainable
2	25.1– 50.0	less	less sustainable
3	50.1–75.0	quite	fairly sustainable
4	75.1–100.0	good	sustainable

Table 3: Parameter values of the leverage factor

No.	Factor value	Category	Description
1	<2.0%	Neutral	Not Influential
2	2-8%	Influential	Moderate to Good Impact
3	>8.0%	Significant	Dominant

ensure calculation stability and minimize variability. By considering variations in expert judgments, dimension weightings, and changes in input data, the sensitivity analysis assessed their impact on sustainability scores, thereby guaranteeing the consistency and reliability of the outcomes. If the difference between the MDS value and the Monte Carlo value is small (<5%), it indicates that the MDS analysis for determining sustainability is sufficiently accurate with a 95% confidence level.

RESULTS AND DISCUSSION

Identification of the attributes in each dimension of sustainability by scientific judgment will determine the accuracy of the estimation of the level of the sustainability index. An attribute's definition should be clear and encompass its temporal aspects. The 33 attributes of all dimensions consist of environmental, economic, social, technological, and institutional, presented in Table 4.

Index sustainability of waste management

A questionnaire was designed to evaluate the sustainability level at various stages of waste management, detailing the attributes of each dimension, and was subsequently reviewed by qualified scientific experts. Furthermore, the expert's assessment results were analyzed using the MDS method with the Raffish software. The final result of the estimation of the sustainability index are presented in Table 5 and Fig. 4.

Environmental dimension

The ordination result index for the sustainability status of integrated waste management at TPST / TP3R Banyumas Regency in the Environmental dimension is 47.17%. Based on the value parameter, it is categorized as less sustainable. The sustainability position of the environmental category is presented in Fig. 5. Attributes that play a crucial role in determining the sustainability status of the studied environmental category and can advance sustainability in that dimension are those with a root mean square (RMS) greater than 2. These attributes are organic waste treatment (RMS=4.61) and recycling rate (RMS=2.51). Organic waste management is an essential component of sustainable environmental management. The impact on the environment, especially the agricultural environment, waste can have an impact on reducing the quality of the soil and of course greatly affects the results of agriculture, and affects farmers' income. Improper management of organic waste, including food waste, garden refuse, and other biodegradable materials, can result in problems such as littering, air contamination, and increased greenhouse gas emissions. Organic waste management requires an integrated approach and involves various parties, including the community, government, and industry. With the right technology and high awareness of the importance of biodegradable waste management, the negative impact of organic waste on the environment will reduce and at the same time utilize its potential to become a useful resource. The integrated system's success is instrumental in guiding decisions related to resource distribution and in planning for the sustainability of waste management practices. Garbage banks are a possible community-based waste handling solution (Asteria and Heruman, 2016).

While the efficiency of traditional waste treatment methods can differ, they are capable of effectively eliminating various toxins from both soil and water.

Table 4: List of dimensions and their attributes

Environmental	Economy	Social	Technology	Institutional
1. Waste Reduction 2. Recycling Rate 3. Organic Waste Treatment 4. Hazardous Waste Management 5. Air Quality Around Waste Treatment Plants 6. Land Use Efficiency at Waste Treatment Plants 7. Rainwater Management at Waste Treatment Plants 8. Leachate Water Quality	9. Operational Funding 10. Waste Contribution Fee 11. TPS3R/TPST Income 12. Government and Other Subsidies 13. Equipment Maintenance Budget	14. Community Concern for Waste Management 15. Environmental Education 16. Management Services 17. Community Health Around Landfill 18. Gender Contribution 19. Community Conflict	20. Service coverage (Banyumas area) 21. Service coverage (Purwokerto area) 22. Integrated waste management at TPS3R/TPST and TPA 23. Organic waste processing into RDF 24. Organic waste processing into BSF maggots 25. Combustible waste processing into RDF 26. Plastic waste processing into building materials 27. Residual waste processing through burning 28. Final processing site 29. Waste data inventory	30. Leadership and Institutional Structure 31. Role and authority of the Environmental Service officer 32. Community Groups 33. Inter-Institutional Cooperation

Table 5: The results of the index of sustainability for every element and Associated accuracy requirements

Dimension	Index (%)	SQR	R^2 Stress
Environmental	47.17	0.9339	0.230
Social	52.12	0.9346	0.245
Economy	55.27	0.9344	0.246
Technology	54.44	0.9354	0.223
Institutional	45.10	0.9247	0.263
Average	50.82		

One of the primary causes of cultural eutrophication is the discharge of family trash into freshwater bodies. Agriculture can use organic debris floating in wastewater as a source of nutrients (Koul *et al*., 2022). Conventional methods for the extraction and recycling of organic materials and wastewater may encourage the sustainable management of water resources moving forward (Rohmanna and Maharani, 2022). These days, scientists are looking for an organic waste management technique that is both economical, environmentally friendly, and advantageous to society as a whole. In the context of organic waste management, vermiculture is emerging as a promising and sustainable technique for waste treatment, indicating a positive outlook ahead (Rachman *et al*., 2016). Since all of the waste produced was recycled, lowering emissions from landfills could be less expensive. Recycling construction

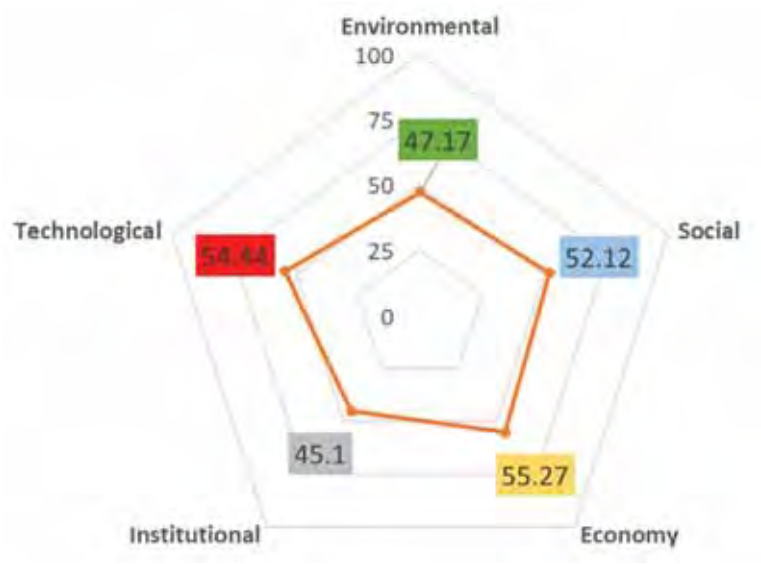


Fig. 4: Sustainability status of waste management program

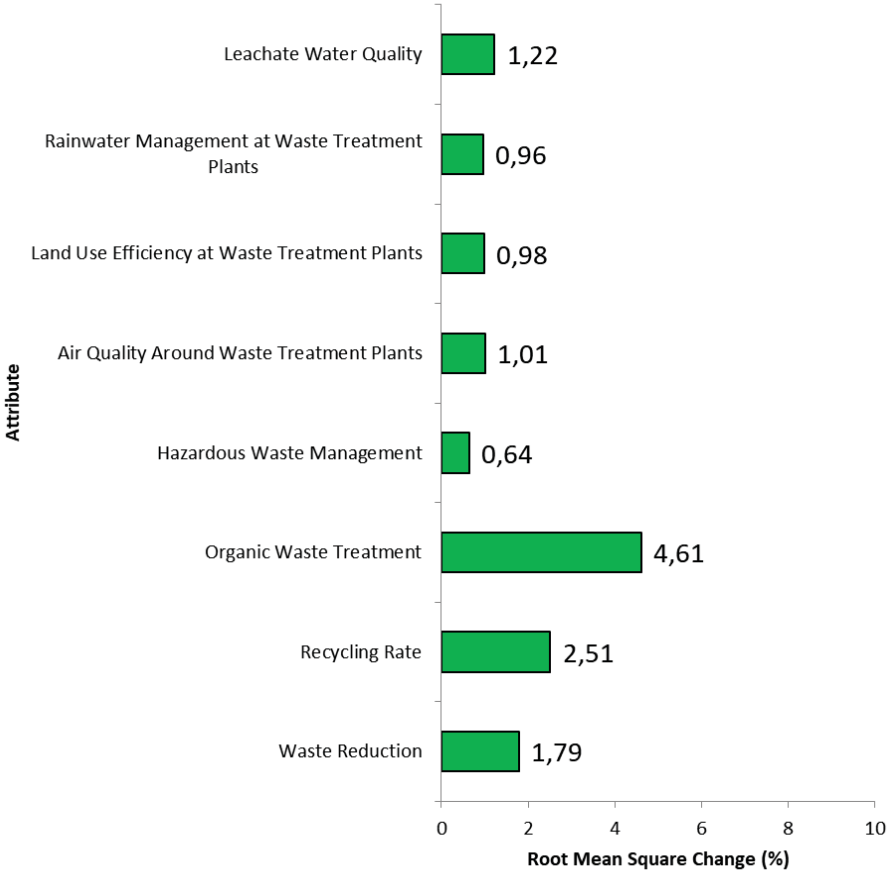


Fig. 5. Leverage of environment attributes

and demolition trash was strongly advised for long-term economic and environmental stability due to the anticipated benefits to the environment and economy (Berenjkar *et al.*, 2021). Improving recycling rates in waste management is a challenging endeavor; however, it is vital for mitigating harmful environmental effects and promoting the reuse of essential resources. Industries, governments, and communities have to collaborate closely to address the problem of increasing recycling rates in trash management. To boost environmental sustainability and minimize landfill waste, it is essential to increase public awareness, improve recycling facilities, establish supportive regulations, and leverage advanced technologies.

Social dimension

The social sustainability index for Banyumas district's waste management system, at 52.12%, reflects a moderate level of advancement, as indicated by a MDS analysis. Several social attributes contribute to this score, with the community's focus on waste management exerting the strongest influence at 2.23%, thereby making it the most influential factor (Fig. 6). Attributes like community conflict (1.33%), gender contribution (1.06%), and community health around landfills (0.82%) also contribute, though to a lesser extent, while factors such as environmental education (0.04%) have minimal impact, pointing to potential gaps in public awareness and education efforts (Godfrey *et al.*, 2020; Muktiningsih *et al.*, 2023). The strong impact of community awareness highlights the importance of public participation in advancing social sustainability within waste management practices. When communities are invested in waste issues, they are more likely to participate in activities like recycling and responsible disposal, which strengthen the system's sustainability. Strengthening community awareness, possibly through specialized educational campaigns or collaborative initiatives, could enhance the effectiveness of this attribute, motivating the local population to adopt sustainable waste management practices (Sewak *et al.*, 2021). Moreover, research by Permana *et al.* (2015) found that community practices like waste reduction and separation were

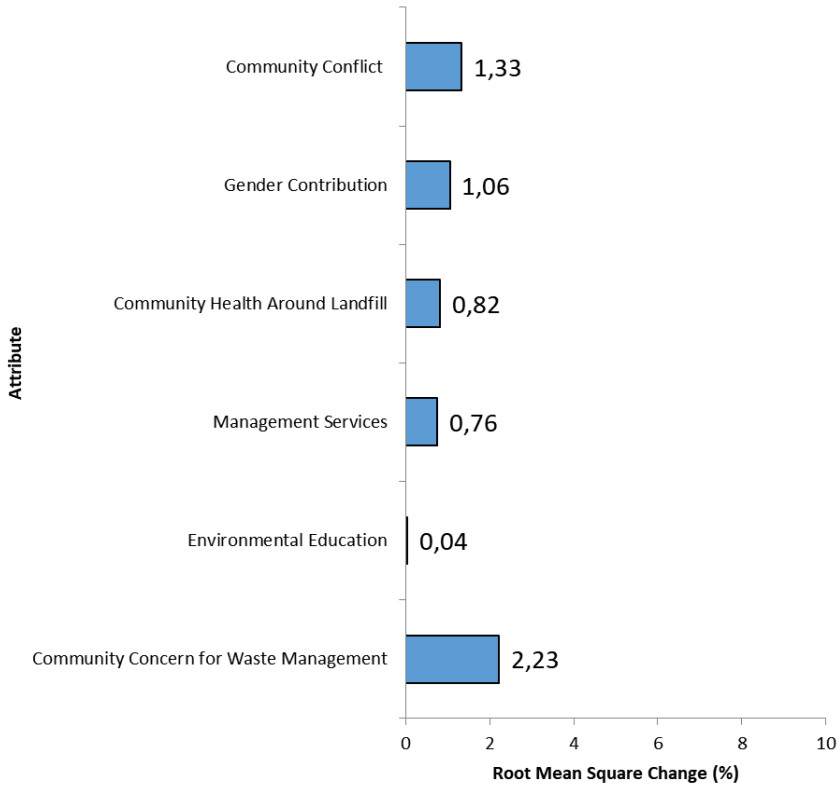


Fig. 6: Leverage of social attributes

closely linked to a collective sense of community cleanliness. Lower leverage for environmental education and service management implies that existing educational efforts are insufficient to make a meaningful social impact, potentially due to limited reach or engagement strategies (Nieves and Delgado Ramos, 2023; Idawati et al., 2024). Expanding community education initiatives will enable us to tackle this problem and foster lasting changes in waste disposal practices (Godfrey *et al*., 2020). To enhance social sustainability, the district might consider launching focused educational initiatives aimed at raising awareness of proper disposal methods. This could involve utilizing local campaigns, organizing workshops, and collaborating with schools to encourage community engagement. Establishing waste management committees could provide platforms for resolving conflicts and engaging diverse demographic groups, particularly in areas close to landfills. Providing incentives, including tax incentives or grants for community engagement, has the potential to increase participation, especially with an inclusive framework that highlights the importance of gender representation in waste management efforts (Rachman *et al*., 2016). Through these interventions, Banyumas could strengthen community support for sustainable waste practices, creating a cohesive, community-driven approach to waste management. Sustainable waste management in low-resource settings faces challenges such as inadequate infrastructure, weak policy enforcement, and limited public awareness (Kaza *et al*., 2018). Inadequate funding for waste collection and treatment commonly results in ineffective landfill operations and open dumping, thereby escalating risks to both the environment and public health. Context-specific policy interventions, including EPR and public-private partnerships (PPPs), can mobilize funding and improve waste processing infrastructure, as demonstrated in South Korea and Sweden (Hwang and Kim, 2022). In Indonesia, community-operated waste banks have shown to be effective in boosting recycling rates and promoting active participation among residents (Muktiningsih *et al*., 2023). Additionally, innovative approaches such as WTE technologies and micro-financing for small-scale recycling enterprises can enhance efficiency and economic opportunities in waste management (Sulaiman *et al*., 2021). Well-designed environmental education efforts can raise public consciousness and promote lasting involvement in sustainable waste practices. Hands-on learning activities, such as waste segregation workshops and recycling programs, encourage community participation and behavior change (Godfrey *et al*., 2020). Incorporating waste education into educational programs helps develop early awareness, a key factor for long-term sustainable waste management. Digital campaigns, including social media outreach and mobile apps, can expand educational reach, making waste management information more accessible (Sulaiman *et al*., 2021). Additionally, government policies that mandate waste education and training for businesses and households can institutionalize behavioral change, leading to broader adoption of sustainable practices (Rachman *et al*., 2016).

Economic dimension

The economic sustainability index for Banyumas district's waste management system, at 55.21% based on MDS, reflects a moderate level of economic viability with potential for growth. Key economic contributors, such as TPS3R/TPST income (8.83%), and waste contribution fee (7.33%) demonstrate influential leverage but remain within the "influential" range (2-8%) (Fig. 7). Notably, TPS3R/TPST income at 8.83%, show the highest leverage, underscoring the need for robust governance to drive economic efficiency in resource allocation and policy execution in the waste management sector (Kurniawan *et al*., 2021). Improving economic sustainability in Banyumas' waste management system could be beneficial to implement specific leadership development initiatives and forge strategic partnerships. Leadership and environmental service officers could benefit from training in resource management, financial accountability, and strategic planning, enhancing their ability to make informed economic decisions that optimize financial resources in waste management (Owusu-Acheampong *et al*., 2024). By formalizing cooperation between institutions via MOUs and structured partnerships, agencies can synchronize their objectives, optimize resource allocation, eliminate redundancy, and amplify the economic outcomes of their collaborative projects (Fariz *et al*., 2024). This approach is critical for streamlining resources across public and private sectors while encouraging consistent goal alignment

(Godfrey *et al.*, 2020). To further support local economic contributions, financial incentives for community TPS3R groups, such as micro-financing and subsidies, could enhance waste processing and recycling efforts, generating economic value and job opportunities at the community level (Muktiningsih *et al.*, 2023). By applying economic performance metrics in these community-operated facilities, it is possible to gather crucial data that can help optimize expenses and track income, ultimately strengthening economic resilience. Circular economy principles enhance waste management sustainability by minimizing waste generation, extending product life cycles, and promoting material reuse and recycling. The process of waste valorization, involving the production of bioenergy, composting, and upcycling, boosts long-term resource efficiency, lessens environmental harm, and fosters economic opportunities. Integrating these approaches strengthens financial resilience while fostering a more sustainable and resource-efficient waste management system. Financial planning plays a crucial role in sustaining waste management by ensuring balanced economic, environmental, and social priorities. Strategies such as EPR, PPP, and waste tariffs help stabilize funding, while investments in recycling infrastructure and WTE technologies enhance financial resilience and long-term sustainability (Kurniawan *et al.*, 2021; Godfrey *et al.*, 2020). The adoption of these specific strategies will enable Banyumas' waste management system to bolster its economic sustainability, aligning with Indonesia's overarching aims for sustainable waste management and economic development.

Technological dimension

The technological sustainability of Banyumas district's waste management system stands at a moderate 54.44%, with MDS analysis identifying service coverage as a critical factor. Service coverage in the Purwokerto district (2.25%) is the most influential attribute, reflecting its essential role in addressing waste management needs as urban areas expand (Fig. 8). In comparison, various technological elements, including pre-treatment equipment, incinerator, plastic waste processing, organic waste composting using black soldier flies, refuse-derived fuel, are essential for achieving sustainable management goals (Febijanto *et al.*, 2024; Pratama *et al.*, 2025; Wahyono *et al.*, 2023). Enhancing service coverage has the potential to significantly improve sustainability, as it reduces the volume of uncollected waste, thereby minimizing environmental pollution.

Technological sustainability enhances social engagement by improving waste management

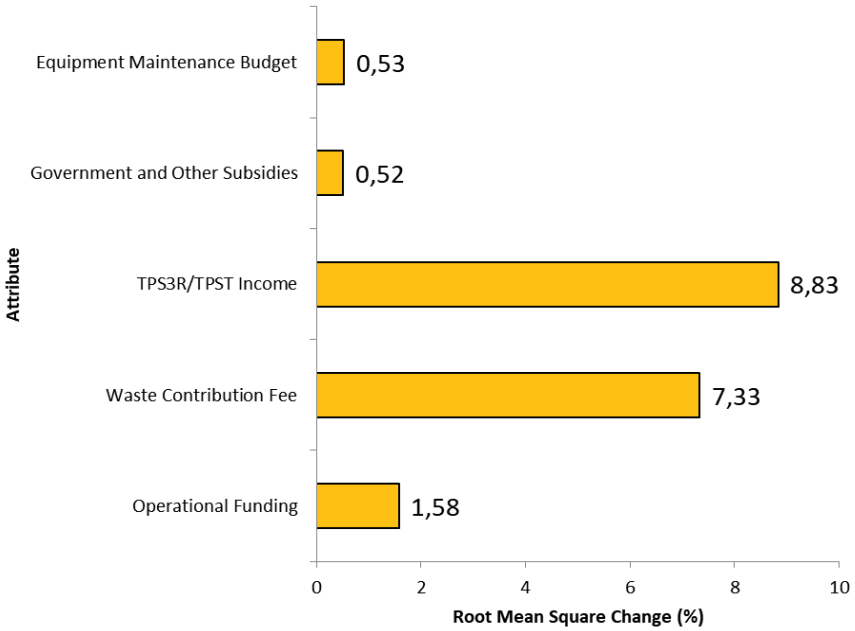


Fig. 7: Leverage of economic attributes

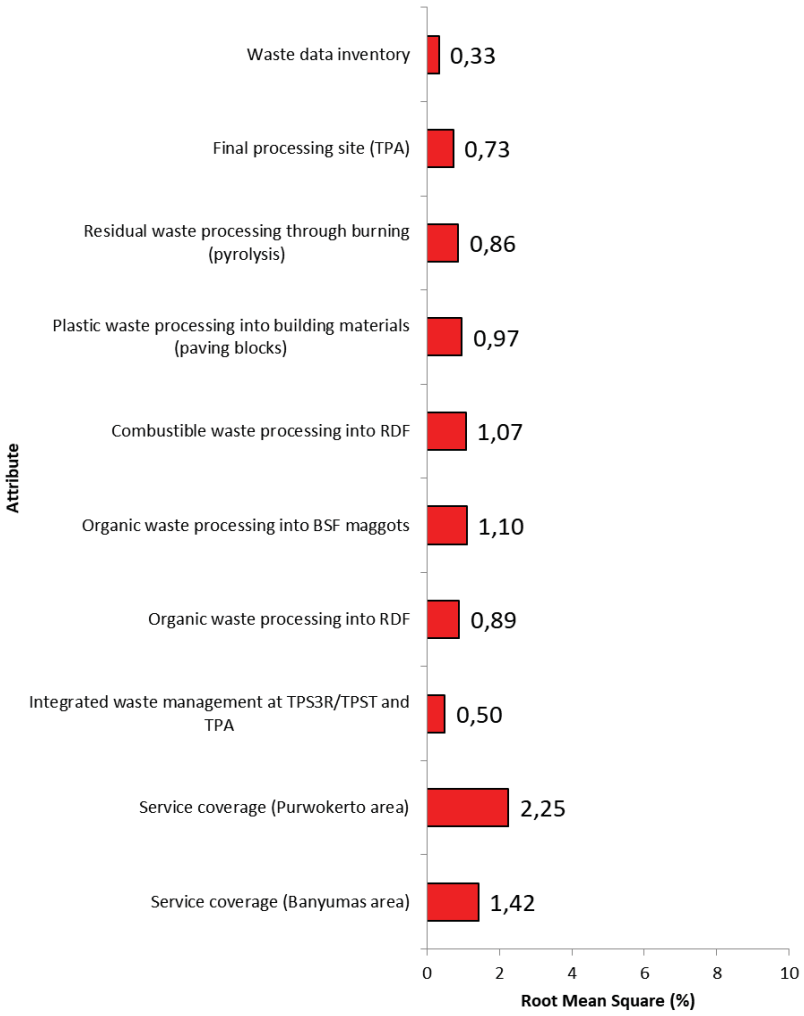


Fig. 8: Leverage of technology attributes

efficiency and accessibility. Innovations like smart waste collection systems, recycling technologies, and digital platforms enhance the efficiency of waste management, promoting higher levels of public engagement. When waste services become more reliable and user-friendly, communities are more likely to engage in sustainable practices, strengthening social responsibility in waste management. Implementing mobile collection units in underserved regions and using Internet of thing (IoT)-based tracking for efficient collection can help achieve these goals, mitigating health risks and enhancing the reach of disposal management services (Ahmad *et al.*, 2015; Sulaiman *et al.*, 2021). As urban areas continue to expand, implementing these measures becomes vital for sustaining efficient waste management practices. Technological advancements such as WTE systems (Kristiawan *et al.*, 2021), IoT-based waste tracking, and bioconversion using black soldier fly larvae can enhance waste processing efficiency and recycling rates (Muktiningsih *et al.*, 2023). By employing automated sorting technologies and AI-powered material recovery facilities, waste segregation is improved, resulting in lower contamination levels and a higher value of recyclable materials (Nieves and Delgado Ramos, 2023). Integrating these innovations into existing systems requires government incentives, PPP, and capacity building, ensuring cost-effective and scalable adoption in Banyumas' waste management infrastructure. Providing financial support through

subsidies or low-interest loans for facilities that engage in plastic repurposing and organic composting can encourage their broader implementation. Community engagement and awareness campaigns could also encourage public support for these technologies, reinforcing the sustainability of the system's technological infrastructure. Adopting these interventions, Banyumas can enhance its waste management resilience and continue progressing towards sustainable, technologically supported waste management (Nieves and Delgado Ramos, 2023; Muktiningsih *et al*., 2023).

Institutional dimension

With an MDS-derived index of 45.1%, the institutional sustainability of the waste management system in Banyumas district reveals a lower level of sustainability, suggesting opportunities for enhancement. Key attributes, including leadership and institutional structure (4.71%) and inter-institutional cooperation (3.68%), are moderately influential (Fig. 9).

To align policies and operations effectively and to cut down on inefficiencies, it is imperative to have robust governance and collaborative structures that engage agencies, non-governmental organizations (NGOs), and the private sector (Kurniawan *et al*., 2021). Community groups managing TPS3R facilities (3.17%) also play a vital role, emphasizing local involvement in waste segregation, which is particularly significant in semi-urban and rural areas (Rachman *et al*., 2016). To enhance the institutional sustainability of Banyumas, it is essential to strengthen leadership by implementing training programs that develop skills in resource management, policy execution, and sustainable governance practices. Formalizing inter-institutional partnerships with memorandums of understanding (MOUs) can strengthen collaborative efforts, clearly delineating roles and ensuring a unified approach to waste management goals (Fariz *et al*., 2024). To improve inter-agency partnerships, it is essential to establish formal agreements, ensure transparent coordination, and promote shared accountability. Memorandums of understanding (MOUs) establish clear roles among government bodies, NGOs, and community groups, ensuring efficient resource allocation and policy alignment (Fariz *et al*., 2024). PPPs in countries like South Korea and Sweden have demonstrated the effectiveness of structured collaboration, improving recycling rates and WTE initiatives. Enhancing operational efficiency and ensuring long-term sustainability in Banyumas can be achieved by bolstering institutional collaboration through regulatory reforms, innovative funding mechanisms, and the implementation of digital tracking platforms (Liu *et al*., 2025). The

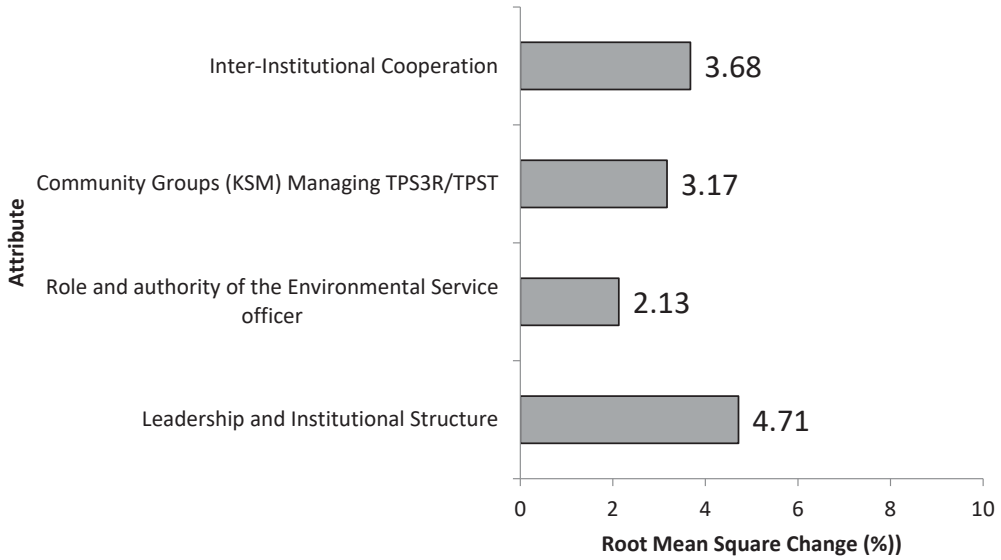


Fig. 9: Leverage of institutional attributes

government plays a pivotal role in ensuring the success of these policies by fostering a supportive regulatory environment and actively facilitating private sector participation. Overcoming existing challenges requires the establishment of effective governance mechanisms, which include clear regulatory frameworks, transparent permitting processes, and comprehensive monitoring systems. Improving coordination among relevant ministries and local governments can help eliminate regulatory inconsistencies and streamline waste management policies. Moreover, the government can enhance private sector involvement by establishing targeted funding programs and providing capacity-building initiatives for small and medium-sized enterprises in the recycling industry. Campaigns designed to enhance public awareness and involve the community are essential for encouraging sustainable waste management habits and guaranteeing the enduring effectiveness of policies. For TPS3R community groups, technical training in waste segregation and waste-to-resource conversion can boost operational efficiency, aiding local recycling and segregation efforts (Muktiningsih *et al*., 2023). Improvements in policy can further strengthen the position of environmental service officers by enabling them to enforce regulations effectively and foster community awareness regarding waste practices. Additionally, incentives like subsidies for community recycling initiatives or financial support for TPS3R facilities can drive local engagement and foster a more resilient waste management ecosystem (Ismiraj *et al*., 2023; Agamuthu and Babel, 2023). The purpose of these combined initiatives is to enhance the institutional framework of Banyumas, creating a sustainable model capable of tackling wider waste management issues. Policy gaps in waste management governance lead to inefficiencies, weak enforcement, and low stakeholder engagement, hindering sustainable waste practices. Strengthening governance mechanisms through regulatory reforms, EPR policies, and decentralized management can improve institutional effectiveness (Chen *et al*., 2025). Countries like South Korea and Sweden have seen improvements in waste processing efficiency through PPP. Furthermore, the implementation of digital waste tracking platforms enhances transparency and aids in better decision-making (Liu *et al*., 2025). Enhancing leadership and governance in waste management requires capacity building, decentralized governance, and regulatory reforms. Training environmental officers in financial management and strategic planning strengthens decision-making and institutional effectiveness (Kurniawan *et al*., 2021). By delegating waste management responsibilities to local governments and communities, efficiency is improved and public engagement is promoted, as illustrated by the waste bank initiatives in Indonesia (Muktiningsih *et al*., 2023). PPPs, such as those implemented in South Korea and Brazil, improve resource allocation and service delivery (da Silva and Elfany, 2021). PPP enhance waste management governance by leveraging private sector investment and expertise. Successful models in South Korea and Sweden have improved recycling rates and WTE initiatives, while India and Brazil have used PPPs to formalize waste collection and resource recovery (Sverige, 2021; da Silva *et al*., 2021). These collaborations improve efficiency, reduce landfill dependency, and foster economic sustainability in waste management. Moreover, dependable funding mechanisms, like waste tariffs and subsidies, play a key role in ensuring the sustainability of waste programs in regions that lack adequate funding (Kaza *et al*., 2018). Enhancing institutional sustainability requires improvements in key supporting factors, with leadership and institutional structure being the most critical, followed closely by inter-institutional cooperation. Enhancing these factors, especially the collaboration among institutions, requires a robust strategy that includes effective communication, cooperative planning, and transparent assessment. Successful cooperation hinges on aligning common goals, clarifying roles, and ensuring that resources and policies are in place to facilitate collaboration (Adawiah *et al*., 2024). Strong partnerships and the success of collaborative efforts depend on effective coordination among the public, private, and community sectors. Improving leadership and institutional structure attributes can be achieved by enhancing institutional frameworks, reinforcing regulations, boosting community involvement, and ensuring adequate funding. Leaders' active engagement and government initiatives significantly contribute to a region's success. Furthermore, organizational path dependencies indicate that local waste policies in both democratic and authoritarian regimes are influenced by decisions made by higher levels of government in the past (Abdelsalam *et al*.,

2021). Waste management in Banyumas will find it difficult to attain the desired sustainability level unless this institutional aspect is properly addressed. An example of successful waste management in Depok, West Java, Indonesia can be seen through qualitative fieldwork. The findings suggest that the transformation of Depok's waste management occurred due to a series of policies implemented by the mayor in collaboration with the Depok City Government from 2006 to 2016. This situation highlights the importance of effective leadership in cultivating creative policies aimed at resolving societal issues. The vision of the leader was successfully turned into policy and carried out by bureaucratic institutions, leading to significant changes in the region. Additional key factors include the credibility of the leadership, protection from opposition, and access to necessary resources. Additionally, emphasize the crucial role of leadership in demonstrating effective waste management practices such as reduction, reuse, recycling, and community engagement to local populations. The ability of the leader to unite his ideas within the community and his commitment to sustainable change were crucial to the success of these policies (Azizah *et al*., 2021).

RECOMMENDATION

Enhancing environmental sustainability in Banyumas requires strengthening institutional frameworks, leadership, and inter-institutional coordination. Enhancing training programs for environmental officers and boosting financial assistance for community-based waste management organizations like TPS3R can foster greater community involvement in waste segregation and decrease reliance on landfills. Partnerships with NGOs and the private sector can optimize resource allocation and enhance environmental impact, supporting landfill diversion and pollution reduction (Fariz *et al*., 2024; Kurniawan *et al*., 2021). Strategic investments in leadership training, financial planning, and resource management are essential for fostering economic sustainability. Incentives, including grants, subsidies, and micro-financing, can strengthen TPS3R groups, promoting local recycling and creating employment opportunities. Structured inter-institutional collaborations improve financial accountability and streamline resource allocation between public and private stakeholders (Muktiningsih *et al*., 2023). Increasing awareness and education about waste management among the public is vital for fostering improving social sustainability. Targeted campaigns and school-based programs can bridge knowledge gaps and encourage long-term behavioural change. The creation of community waste committees aids in resolving conflicts and ensures that participation is diverse, including representation from different genders. Financial incentives, such as tax reductions for active participation, foster a community-driven waste management culture (Godfrey *et al*., 2020; Rachman *et al*., 2016). Advancing technological sustainability requires improved service coverage, particularly in underserved areas. Mobile waste collection units and IoT-based tracking systems optimize waste collection efficiency and minimize uncollected waste, reducing environmental health risks. By extending low-interest loans or subsidies to bolster financial support for plastic recycling and organic composting projects, we can expedite the implementation of sustainable waste technologies, thereby creating a more resilient waste management infrastructure (Ahmad *et al*., 2015; Sulaiman *et al*., 2021). Institutional sustainability can be strengthened through leadership development and structured governance reforms. Partnerships across various agencies, underpinned by memorandums of understanding, strengthen the collaboration between government organizations, NGOs, and private sector partners. Strengthening the authority of environmental service officers and providing specialized training for community-based waste groups improve operational efficiency and promote sustainable waste processing practices (Ismiraj *et al*., 2023; Agamuthu and Babel, 2023). Achieving long-term sustainability in the waste management system of Banyumas requires the development of thorough strategies that integrate governance, financial stability, community participation, technological innovation, and cooperation between institutions.

CONCLUSION

This study assessed the sustainability of Banyumas district's waste management system using the MDS approach, evaluating environmental, economic, social, technological, and institutional dimensions. The results show a moderate level of advancement in all areas; however, significant gaps persist, especially in the environmental, economic, and institutional

sectors. The environmental sustainability index at 45.1% reflects challenges in waste diversion and landfill reduction. Institutional attributes, including leadership (4.71%) and inter-institutional cooperation (3.68%), contributed positively but lacked sufficient influence to drive significant improvements. Enhancing governance frameworks and leadership capabilities is crucial for improving the efficiency of waste management processes. The economic dimension, with a sustainability index of 55.27%, highlighted resource allocation and financial resilience as critical concerns. While income from TPST facilities provided leverage, weak fiscal management within community-based waste programs limits long-term financial stability. Enhancing governance by means of training and strategic collaborations can lead to better resource management, boost economic participation, and establish reliable revenue sources for sustainable waste programs. The social dimension scored 52.12%, with community participation identified as a key driver of sustainability. Public engagement in waste management, particularly concern for waste practices (2.23%), demonstrated moderate leverage. However, gaps in environmental education suggest a need for targeted awareness programs to strengthen long-term public commitment. Technological sustainability, scoring 54.44%, reflected moderate advancements, with service coverage identified as a critical area for improvement. To mitigate environmental threats and boost service effectiveness, it is crucial to extend waste collection in areas experiencing rapid urbanization. Support for plastic waste processing and organic composting technologies would improve repurposing efforts and reinforce the technological infrastructure of the waste management system. With a score of 45.1%, institutional sustainability underscored the significance of effective leadership and systematic inter-agency coordination in boosting operational efficiency. Strengthening formal partnerships, clarifying roles between government and non-government stakeholders, and providing technical training for TPS3R community groups could enhance institutional effectiveness in waste segregation and recycling. The waste management system in Banyumas shows advancements in sustainability initiatives; however, it needs specific interventions to ensure lasting effectiveness. Strengthening governance capacity, fostering financial resilience, enhancing community participation, expanding technological applications, and improving institutional coordination are essential strategies. These measures will enable Banyumas to establish a more efficient, sustainable waste management system aligned with Indonesia's environmental and economic objectives.

AUTHOR CONTRIBUTIONS

Y. Ismail conducted a thorough analysis of the manuscript's substantial worth; R. Adji assisted with experimental; A.D. Santoso as a corresponding author and conducted the oversaw the work; S. Wahyono analysed and interpreted the data; M.A. Kholiq supervised written works; T. Handayani was responsible for the manuscript's validation; S.D.R. Pahri conducted a literature study and edited the manuscript; S. Putiamini assisted with experimentation and data collection; R.A. Pratama conducted a literature study and edited the manuscript; F. Nurfatriani supervised written works; F.L. Sahwan analyzed and interpreted the data; F. Suryanto assisted with experimental and administrative tasks; Prasetiyadi analyzed and interpreted the data; R.D. Tilottama assisted with experimental and administrative tasks.

ACKNOWLEDGMENTS

The authors are grateful to the Deputy Chairman for Development Policy at the National Research and Innovation Agency (BRIN) of Indonesia for the support the instrumental in facilitating survey activities, FGDs, and obtaining necessary research permits. The authors would like to thank the editors and anonymous reviewers for their constructive feedback.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or

format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit:
http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims with regard to published maps and institutional affiliations.

ABBREVIATIONS

%	Percent
AI	artificial intelligence
AHP	Analytical Hierarchy Process
ASCAL	Multidimensional scaling, other name biside MDS
BSF	Black soldier fly
d	Euclidian distance
dij	Euclidian distance from point i to point j
dijk	Squared distance
EPR	Extended producer responsibility
Eq	Equation
FGD	Focus group discussions
GHGs	Greenhouse gases
HVW	High value waste
IoT	Internet of thing (IoT)
I, J, K	Dimension
LVW	Low value Waste
JAKSTRANAS	National Policy and Strategy for Waste Management
KSMs	Community self-help groups
MDS	Multidimensional scaling
MOUs	Memorandums of Understanding
MSW	Municipal solid waste
MSME	Micro Small Medium Enterprise
NGOs	Non-Government Organizations
Oij	Point of origin
PPPs	public-private partnerships
Rapfish	Rapid appraisal for fisheries
R2 Stress	Coefficient of Determination and dissimilarities
RDF	Refuse Derived Fuel
RMS	Root mean square
S	Stress
SQR	Structured query reporter
SALIMAS	Sampah online banyumas android-based waste management aplication
t/day	Ton per day
TPA	Final disposal sites
TPS3R	Waste management stations and recycling center
TPST	Waste management stations
WTE	Waste-to-energy
y	Year

REFERENCES

Abdelsalam, M.K.; Egdair, I.M.M.; Begum, H.; Md. Jadi, D.; Al Issa, H.-E.; Abrika, O.S.S.; Alam, A.S.A.F., (2021). The key organizational factors in healthcare waste management practices of Libyan public hospitals. Sustainability. 13, 12785:1-19 (**19 pages**).

Adawiah, W.; Hanindraputri E.; Kamalsyah, M., (2024). Leadership, innovation and community participation pillar of institutionalization in bank sampah induk Surabaya. J. Social Dyn. Governance, 1(2):111-119 (**9 pages**).

Agamuthu P.; Babel S., (2023). Waste management developments in the last five decades: Asian perspective. Waste Manage. Res., 41(12): 1699-1716 (**19 pages**).

Ahmad, S.Z.; Ahamad, M.S.; Yusoff, M.S., (2015). A comprehensive review of environmental, physical and socio-economic (EPSE) criteria for spatial site selection of landfills in Malaysia. Appl. Mech. Mater, 802:412-418 **(7 pages)**.

Allaily A.; Santoso, A.D.; Rofiq, M.N.; Sasongko, N.A.; Daulay, H.; Wiloso, E.I.; Widjaja, E.; Utomo, B.N.; Yanuar, A.I.; Suryani, S., Erlambang, Y.; Thiyas, U.; Iskandar, D.; Anhar, A.; Rahmawati, M.; Simamora, T.; Yusriani, Y.; Maghfirah, G.; Ammar, M., (2024). Sustainability assessment of animal feed production from by-products of Sago palm smallholder industry. Global J. Environ. Sci. Manage., 10(3): 1275-1296 (**22 pages**).

Asteria, D.; Heruman, H., (2016). Waste Banks as an alternative of community-based waste management strategy in Tasikmalaya. J. Manusia Dan Lingkungan, 23(1): 136-141 (**6 pages**).

Azizah, N.; Astrina, A. R.; Ulfa, N., (2021). Leadership and city waste politics: A case study on the waste management in Depok city,

West Java Province 2014 – 2017. PCD J. 9(1): 65-82 (**18 pages**).
Berenjkar, P.; Li, Y.Y.; Yuan, Q., (2021). The application of system dynamics in different practices of a waste management system. Environ. Dev. Sustainable. 23: 15695–15724 (**30 pages**).
Bakrie, B.; Sirnawati, E.; Rohaeni, E.S.; Hutahaean, L.; Santoso, A.D.; Wasito, W.; Indrawanto, C., (2023). Sustainability analysis of intensive duck farming system in Sliyeg District, Indonesia: MDS and MICMAC analysis approach. Intl. J. Sustainable Dev. Plann., 18(10): 3181-3193 (**13 pages**).
Central Bureau of Statistics, (2023). Population estimation of Central Java Province. Central Bureau of Statistics.
Chairani, C.; Martono, D.N.; Wahyono, S., (2023). Alternative Locations for TPS 3R (Study: Purwokerto Kulon Village, Banyumas Regency). J. Penelitian Pendidikan J. Penetitian Pendidikan. 9(1): 36–41 **(6 pages).**
Chen, Y.; Fang, Y.; Wang, T.; Liu, R.; Sandylove, A.; Peng, S.; Wu, X.; Yang, P., (2025). Has environmental sociology research effectively responded to the urgent need for environmental governance in China? A study based on bibliometric analysis. Sustainability, 17(6): 2335(**20 pages**).
da Silva, M.; Elfany, R., (2021). Solid waste management and contemporary challenges, Revista Nacional de Gerenciamento de Cidades, 9: 17271 (**11 pages**).
Dinis, M.A.; Neto, B.; Begum, H.; Vidal, D.G., (2022). Waste challenges in the context of broad sustainability challenges. Front. Environ. Sci., 31(10): 964366 **(3 pages)**.
Eric, K.I., (2024). Prioritizing food waste management for a greener tomorrow beyond landfills: strategies to shrink our carbon footprint through food waste reduction. Asian J. Environ. Ecol., 23(7), 37-48 **(12 pages)**.
Fairuzia, N.; Krisnamurthi, B.; Rifin, A., (2020). Analysis of sustainability status of cocoa plantation smallholders. IOP Conference Series: Earth Environ. Sci., 486: 012001 **(8 pages).**
Fariz, R.D.A.; Muis, R.; Anggraini, N.; Rachman, I.; Matsumoto, T., (2024). Good environmental governance roles in sustainable solid waste management in indonesia: A review. J. Community Based Environ. Eng. Manage., 8(8), 45-56 **(12 pages)**.
Febijanto, I.; Steven, S.; Nadirah, N.; Bahua, H.; Shoiful, A.; Dewanti, D.P.; Kristyawan, I.P.A.; Haris, K.A.; Yuliani, M.; Hanif, M.; Robbani, M.H.; Yusuf, N.R.; Prihartanto, Alfatri, P., Pratama, R.A.; Purwanta, W.; Wiharja, W.; Nugroho, R.; Ramadhan, S.K., (2024). Municipal solid waste (MSW) reduction through Incineration for electricity purposes and Its environmental performance: A case study in Bantargebang, West Java, Indonesia. Evergreen. 11(1): 32–45 (**14 pages**).
Ferdinan; Utomo, S.W.; Soesilo, T.E.; Herdiansyah, H., (2022) Household waste control index towards sustainable waste management: A study in Bekasi City, Indonesia. Sustainability, 14(21): 14403 **(20 pages).**
Ferronato, N.; Torretta, V., (2019). Waste mismanagement in developing countries: A review of global issues. Intl. J. Environ. Res. Public Health. 16(6): 1060 **(28 pages).**
Godfrey, L.; Ahmed, M.T.; Gebremedhin, K.G.; Katima, J.H.; Oelofse, S.; Osibanjo, O.; Richter, U.H.; Yonli, A.H., (2019). Solid waste management in Africa: Governance failure or development opportunity. Reg. Develop. Africa. 10: 5772 **(14 pages)**.
Hadinata, F.; Damanhuri, E.; Rahardyan, B.; Widyarsana, I.M., (2018). Identification of initial settlement of municipal solid waste layers in Indonesian landfill. Waste Manage. Res., 36(8): 737-743 **(7 pages**).
Handayani, T.; Santoso, A.D.; Sastranegara, M.H.; Lestari, S.; Djarot, I.N.; Widyastuti, N.; Nuha, N.; Sitomurni, A.I.; Hadi, A.; Prihatin, A.L.; Suryanto, F., (2025). Assessing the multidimensional sustainability of crystal coconut sugar production in Banyumas Regency, Central Java, Indonesia. Intl. J. Design Nat. Ecodynamics. 20(1): 147-158 (**12 Pages**).
Hwang, H.; Kim, H., (2022). Demand risk transfer and government's cost efficiency: Focusing on Korean waste treatment PPP cases. Waste Manage., 137: 31-38 (**9 pages**).
Idawati, I. ; Sasongko, N.A.; Santoso, A.D.; Septiani, M.; Handayani, T.; Sakti, A.; Purnamasari, B., (2024). Cocoa farmers' characteristics on climate variability and its effects on climate change adaptation strategy. Global J. Environ. Sci. Manage., 10(1): 337-354 **(18 pages)**.
Ismiraj, M.R.; Wulansari, A.; Setiadi, Y.; Pratama, A.; Mayasari, N., (2023). Perceptions of community-based waste bank operators and customers on its establishment and operationalization: Cases in Pangandaran, Indonesia. Sustainability. 15(14): 11052 **(14 pages)**.
Jambeck, J.R.; Geyer, R.; Wilcox, C.; Siegler, T.R.; Perryman, M.; Andrady, A.; Narayan, R.; Law, K.L., (2015). Plastic waste inputs from land into the ocean. Science.3, 347: 768-771 **(4 pages)**.
Kaza, S.; Yao, L.C.; Bhada-Tata, P.; Van Woerden, F., (2018). What a Waste 2.0: A global snapshot of solid waste management to 2050. World Bank Publications.
Khair, H.; Rachman, I.; Matsumoto, T., (2019). Environmental and economic assessment of solid waste bank activities in indonesia: A case study of medan city. J. Japan Soc. Civil Eng., Ser. G: Environ. Res., 75(6): 189-196 (**7 pages**).
Khosravani, F.; Abbasi, E.; Choobchian, S.; Jalili Ghazizade, M., (2023). A comprehensive study on criteria of sustainable urban waste management system: Using content analysis. Sci. Reports, 13(1):22526 (**15 pages**).
Koul, B.; Yadav, D.; Singh, S.; Kumar, M.; Song, M., (2022). Insights into the domestic wastewater treatment (DWWT) regimes: A review. Water. 14(21): 3542 (**29 pages**).
Kurniawan, T.A.; Avtar, R.; Singh, D.; Xue, W.; Othman, M.H.D.; Hwang, G.H.; Iswanto, I.; Albadarin, A.B.; Kern, A.O., (2021). Reforming mswm in sukunan (Yogjakarta, Indonesia): A case-study of applying a zero-waste approach based on circular economy paradigm. J. Cleaner Prod., 284: 124775 (**13 pages**).
Kristyawan, I.P.A.; Wiharja; Shoiful, A.; Hendrayanto, P.A.; Santoso, A.D., (2021). Update on waste reduction performance by waste-to-energy incineration pilot plant PLTSa Bantargebang operations. IOP Conference Series: Earth Environ. Sci., 922: 012059 **(7 pages)**.
Lando, A.T.; Rahim, I.R.; Sari, K.; Djamaluddin, I.; Arifin, A.N.; Sari, A.M., (2021). Estimation of methane emissions from municipal solid waste landfill in Makassar City based on IPCC waste model. IOP Conference Series: Earth Environ. Sci., 841(1): 012002 (**11 pages**).
Lerpiniere, D.J.; Wilson, D.C.; Velis, C.A., (2025). Official development finance in solid waste management reveals insufficient resources for tackling plastic pollution: A global analysis of two decades of data. Resour. Conserv. Recycl., 212: 107918 (**11 pages**).
Lloyd, C.; Ananthan, P.S.; Ramasubramanian, V.; Sugunan, V.V.; Panikkar, P.; Landge, A.T., (2022). Rapid reservoir fisheries

appraisal (r-RAPFISH): Indicator based framework for sustainable fish production in Indian reservoirs. J. Cleaner Prod., 379: 134435 **(17 pages).**

Liu, X.; Zhang, W.; Liu, M.; Han, J., (2025). Green finance & carbon neutrality: strategies and policies for a sustainable future. Frontiers Environ. Sci., 13: 1560927 (**3 pages**).

Lovarelli, D.; Bacenetti, J.; Guarino, M., (2020). A review on dairy cattle farming: Is precision livestock farming the compromise for an environmental, economic and social sustainable production? J. Cleaner Prod., 262: 121409 (**13 pages**).

Matee, S.; Senzia, M., (2023). The impact of poor waste management on public health initiatives in shanty towns in Tanzania. Sustainability. 16(24): 10873 (**26 pages**).

Muktiningsih, S.D.; Sekito, T.; Rahmaudina, S.; Dote, Y.; Prayogo, T.B., (2023). Material flow and waste recovery in a community-based waste management system in Batu, Indonesia. IOP Conference Series: Earth Environ. Sci., 1165(1): 012005 (**12 pages**).

Mulyatna, L.; Yustiani, Y.M.; Andisa, R.R.; Ramadhan, R.F.; Hidayanti, D., (2021). Sustainability analysis of the application of waste bank in elemntery school with a multidimensional scaling approach. J. Community Based Environ. Eng. Manage., 5(2): 103–110 (**8 pages**).

Nieves, A.; Delgado Ramos, G.C., (2023). Advancing the application of a multidimensional sustainable urban waste management model in a circular economy in Mexico City. Sustainabilit., 15(17): 12678 (**23 pages**).

Owusu-Acheampong, E.; Arkaifie, S.J.; Acheampong, J., (2024). Factors affecting succession planning in Sub-Saharan African family-owned businesses: A scoping review. J. Family Bus. Manage., 14(6): 1099-1118 (**20 pages**).

Pandey, A.; Das, N.; Muthu, K.A.; Rao, S.S., (2015). Methanogens in the environment: An insight of methane yield and impact on global climate change. Int. Lett. Nat. Sci., 37:51-60 (**10 pages**).

Permana, A.S.; Towolioe, S.; Aziz, N.A.; Ho, C.S., (2015). Sustainable solid waste management practices and perceived cleanliness in a low income city. Habitat Int., 49: 197–205 (**9 pages**).

Pitcher, T.J.; Preikshot, D., (2001). RAPFISH: A rapid appraisal technique to evaluate the sustainability status of fisheries. Fish. Res., 49(3): 255-270 **(16 pages).**

Pratama, R.A.; Wahyono, S.; Sahwan, F.L.; Suryanto, F.; Hanif, M.; Wiharja; Prihartanto; Prasetiyadi; Suprapto; Tilottama, R.D.; Sarkiwan; Diyono, (2025). Evaluation of the physical and chemical characteristics of waste excavated from an open dump site for sustainable waste management. Case Stud. Chem. Environ. Eng., 11:101069 (**12 pages**).

Rachman, I.; Yustiani, Y.M.; Raharjo, S.; Matsumoto, T., (2016) Analysis on the appropriate model of a community-based waste management: Case of rural area in Karang Joang Village, Balikpapan, Indonesia. Int. J. Waste Resour., 6: 258 (**6 pages**).

Rachman, B.; Ariningsih, E.; Sudaryanto, T.; Ariani, M.; Septanti, K.S.; Adawiyah, C.R.; Ashari; Agustian, A.; Saliem, H.P.; Tarigan, H.; Syahyuti; Yuniarti, E., (2022). Sustainability status, sensitive and key factors for increasing rice production: A case study in West Java, Indonesia. Plos One. 17(12): 1-19 (**19 pages**).

Rimantho, D.; Syaiful, S.; Nurfaida; Sulandari, U., (2022), Electronic waste bank model as a solution for implementing circular economy: Case study DKI Jakarta-Indonesia. Front. Built. Environ., 8:1030196 (**13 pages**).

Rohaeni, E.S.; Ilham, N.; Saptati, R.A.; Rahayu, H.S.P.; Priyono, P.; Anggraeny, Y.N.; Qomariah, R.; Pamungkas, D.; Ermuna, S.S.; Mahendri, I.G.A.P.; Mariyono, M.; Darsani, Y.R.; Hutahaean, L.; Praptana, R.H.; Lesmayati, S.; Ahmad, S.N.; Bahar, S.; Suhartini, S.H.; Santoso, A.D.; Rakhmani, S.I.W., (2024). Developing a sustainable beef cattle business model for smallholder farms in South Kalimantan's drylands. Intl. J. Sustainable Dev. Plan., 19(2): 481-500 (**20 pages**).

Rohaeni, E.S.; Santoso, A.D.; Ariningsih, E.; Widaningsih, N.; Hutahaean, L.; Priyanto, D.; Ilham, N.; Suharyon, S.; Herdis, H.; Widiawati, Y.; Hadiatry, M.C.; Ermuna, S.S.; Mardiharini, M.; Sugandi, D.; Bakrie, B.; Wasito, W., (2023). Analysing the sustainability of swamp buffalo (Bubalus bubalis carabauesis) farming as a protein source and germplasm. Open Agric., 8(1): 20220224 **(23 pages).**

Rohmanna, N.A.; Maharani, D.M., (2022). Waste reduction performance by black soldier fly larvae (BSFL) on domestic waste and solid decanter. Biotropika: J. Trop. Biol., 10(2). 141-145 (**5 pages**).

Salam, M.; Alam, F.; Dezhi, S.; Nabi, G.; Shahzadi, A.; Hassan, S.U.; Ali, M.; Saeed, M.A.; Hassan, J.; Ali, N.; Bilal, M., (2021). Exploring the role of black soldier fly larva technology for sustainable management of municipal solid waste in developing countries. Environ. Technol. Innovation, 24: 101934 **(53 pages)**.

Santoso, A.D.; Hariyanti, J.; Pinardi, D.; Kusretuwardani; Widyastuti, N.; Djarot, I.N.; Handayani, T.; Sitomurni, I.; Apriyanto, H., (2023). Sustainability index analysis of microalgae cultivation from biorefinery palm oil mill effluent. Global J. Environ. Sci. Manage., 9(3): 559-576 (**18 pages**).

Santoso, A.D.; Arianti, F.D.; Rohaeni, E.S.; Haryanto, B.; Pertiwi, M.; Panggabean, L.P.; Prabowo, A.; Sundari, S.; Wijayanti, S.P.; Djarot, I.N.; Kurniawati, F.; Sahwan, F.L.; Prasetyo, T.; Barkah, A.; Adibroto, T.A.; Ridlo, R.; Febijanto, I.; Wasil, A.A.; Lusiana, S.; Rosmeika, R., Heryanto, R. B., (2023a). Sustainability index analysis of organic fertilizer production from paunch manure and rice straw waste. Global J. Environ. Sci. Manage., 9(SI): 193-218 (**26 pages**).

Santoso, A.D.; Handayani, T.; Nugroho, R.A.; Yanuar, A.I.; Nadirah, N.; Widjaja, E.; Rohaeni, E.S.; Oktaufik, M.A.M.; Ayuningtyas, U.; Erlambang, Y.P.; Herdioso, R.; Rofiq, M.N.; Hutapea, R.; Sihombing, A.L.; Rustianto, B.; Susila, I.M.A.D.; Irawan, D.; Iskandar, D.; Indrijarso, S.; Widiarta, G.D., (2023b). Sustainability index analysis of the black soldier flies *(Hermetia illucens)* cultivation from food waste substrate. Global J. Environ. Sci. Manage., 9(4): 851-870 **(20 pages).**

Sewak, A.; Deshpande, S.; Rundle-Thiele, S.; Zhao, F.; Anibaldi, R., (2021). Community perspectives and engagement in sustainable solid waste management (SWM) in Fiji: A socioecological thematic analysis. J. Environ. Manage., 298:113455 (**12 pages**).

Sivaraman, I.; Krishnan, M.; Radhakrishnan, K., (2019). Better management practices for sustainable small-scale shrimp farming. J. Cleaner Prod., 214: 559-572 (**14 pages**).

Sverige, A., (2021). Swedish Waste Management 2021. Swedish Waste Management Association.

Sulaiman, I.A.; Nasution, Z.; Rauf, A.; Kusuma, M.S.B., (2021). Multidimensional scaling approach to evaluate sustainability status of belawan watershed management. IOP Conference Series: Earth and Environ. Sci., 912: 012064 (**8 pages**).

Sumarlin, S.; Purwanto, P.; Syafrudin, S., (2023). Estimation potential of methana gas from Puwatu municipal solid waste

landfill, Indonesia. E3S Web. Conf., 030: 448 42 (**8 pages**).
Wahyono, S.; Sahwan, F.L.; Suryanto, F.; Suprapto; Prasetyadi; Pratama, R.A.; Parlina, I.; Tilottama, R.D.; Sarkiwan; Diyono; Arreza, G., (2023). Identification and analysis of municipal solid waste pre-treatment to improve waste quality for waste-to-energy facility. IOP Conference Series: Earth Environ. Sci., 1201(1): 012008 (**11 pages**).
Widjaja, E., Utomo, B.N.; Santoso, A.D.; Erlambang, Y.P; Surono; Firmansyah, M.A.; Handoko, S.; Erythrina, E.; Rofiq, M.N.; Iskandar, D.; Sasongko, N.A.; Rochmadi, T.; Abbas, N.; Hanif, M.; Garno, Y.S.; Arianti, F.D.; Suretno, N.D.; Askinatin, M.; Hastuti, C.O.I.; Fahrodji, F., (2023). Sustainability index analysis for environmentally low-input integrated farming. Global J. Environ. Sci. Manage. 10(2): 1-20 (**20 pages**).
Widyaningsih, N.L.; Tjiptoherijanto, P.; Widanarko, S.; Seda, F.S.S.E., (2022). Household solid waste management system throuh sustainable consumption. Eco. Develop., 3(2): 48-51 (**4 pages**).
World Bank, (2024). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.
Yusuf, E.S.; Ariningsih, E.; Ashari, Gunawan, E.; Purba, H.J.; Suhartini, S.H.; Tarigan, H.; Syahyuti; Hestina, J.; Saputra, Y.H.; Wulandari, S.; Ilham, N.; Ariani, M., (2022). Sustainability of arabica coffee business in West Java, Indonesia: A multidimensional scaling approach. Open Agric., 7: 820–836 (**17 pages**).

AUTHOR (S) BIOSKETCHES

Ismail, Y., Ph.D., Senior Researcher at Study Program of Environmental Engineering, Faculty of Engineering, President University, Indonesia.
- Email: *yunitaismail@president.ac.id*
- ORCID: 0000-0002-3297-8850
- Web of Science Researcher ID: NA
- Scopus Author ID: 57205019607
- Homepage: https://president.ac.id/

Adji, R., M.Sc., Senior Researcher at Study Program of Agribusiness, Faculty of Business, President University, Indonesia.
- Email: *riyanto.adji@president.ac.id*
- ORCID: 0000-0001-9580-579X
- Web of Science Researcher ID: CAJ-1742-2022
- Scopus Author ID: 58046427500
- Homepage: https://president.ac.id/

Santoso, A.D., Ph.D., Senior Researcher at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
- Email: *arif.dwi.santoso@brin.go.id*
- ORCID: 0000-0003-3595-9265
- Web of Science Researcher ID: HJY-1972-2023
- Scopus Author ID: 56516534000
- Homepage: https://brin.go.id/

Wahyono, S., Ph.D., Senior Researcher at Research Center for Environmental and Clean Technology, National Research and Innovation Agency, Indonesia.
- Email: *sri.wahyono@brin.go.id*
- ORCID: 0000-0002-3524-6815
- Web of Science Researcher ID: NA
- Scopus Author ID: 58502650800
- Homepage: https://brin.go.id/

Kholiq, M.A., Ph.D., Senior Researcher at Directorate of Environment, Maritime, Natural Resources, and Nuclear Policy, National Research and Innovation Agency, Indonesia.
- Email: *muha055@brin.go.id*
- ORCID: 0000-0003-0908-1874
- Web of Science Researcher ID: NA
- Scopus Author ID: 57571226800
- Homepage: https://brin.go.id/

Handayani, T., Ph.D., Professor Research at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
- Email: *titi001@brin.go.id*
- ORCID: 0000-0002-4403-5948
- Web of Science Researcher ID: 8677-2022
- Scopus Author ID: 58170210000
- Homepage: https://brin.go.id/

Pahri, S.D.R., Ph.D., Senior Researcher at Centre for Research in Development, Social and Environment (SEEDS), Faculty of Social Sciences and Humanities, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia.
- Email: *sitidina@ukm.edu.my*
- ORCID: 0000-0002-7684-3739
- Web of Science Researcher ID: AFL-6828-2022
- Scopus Author ID: 56733020600
- Homepage: https://www.ukm.my/portalukm/

AUTHOR (S) BIOSKETCHES

Putiamini, S., Ph.D., Researcher at Directorate of Environment, Maritime, Natural Resources, and Nuclear Policy, National Research and Innovation Agency, Indonesia.
▪ Email: *sepa01@brin.go.id*
▪ ORCID: 0000-0002-3335-1400
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57202967366
▪ Homepage: https://brin.go.id/

Pratama, R.A., M.Sc., Junior Researcher at Research Center for Environmental and Clean Technology, National Research and Innovation Agency, Indonesia.
▪ Email: *reba001@brin.go.id*
▪ ORCID: 0000-0002-2210-296X
▪ Web of Science Researcher ID: KYR-0655-2024
▪ Scopus Author ID: 58563165200
▪ Homepage: https://brin.go.id/

Nurfatriani, F., Ph.D., Senior Researcher at Directorate of Environment, Maritime, Natural Resources, and Nuclear Policy, National Research and Innovation Agency, Indonesia.
▪ Email: *fitri.nurfatriani@brin.go.id*
▪ ORCID: 0000-0002-8422-7477
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 56800957800
▪ Homepage: https://brin.go.id/

Sahwan, F.L., M.Sc., Senior Researcher at Research Center for Environmental and Clean Technology, National Research and Innovation Agency, Indonesia.
▪ Email: *firm001@brin.go.id*
▪ ORCID: 0009-0000-4109-9199
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: NA
▪ Homepage: https://brin.go.id/

Suryanto, F., M.Sc., Senior Researcher at Research Center for Environmental and Clean Technology, National Research and Innovation Agency, Indonesia.
▪ Email: *feddy.suryanto@brin.go.id*
▪ ORCID: 0009-0002-6714-7288
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: NA
▪ Homepage: https://brin.go.id/

Prasetiyadi, M.Sc., Senior Researcher at Research Center for Environmental and Clean Technology, National Research and Innovation Agency, Indonesia.
▪ Email: *pras001@brin.go.id*
▪ ORCID: 0009-0007-6748-8134
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: NA
▪ Homepage: https://brin.go.id/

Tilottama, R.D., B.Sc., Junior Researcher at Research Center for Environmental and Clean Technology, National Research and Innovation Agency, Indonesia.
▪ Email: *regi002@brin.go.id*
▪ ORCID: 0009-0001-3021-8786
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 58563164900
▪ Homepage: https://brin.go.id/

HOW TO CITE THIS ARTICLE

Ismail, Y.; Adji, R.; Santoso, A.D.; Wahyono, S.; Kholiq, M.A.; Pahri, S.D.R.; Handayani, T.; Putiamini, S.; Handayani, T.; Pratama, R.A.; Nurfatriani, F.; Sahwan, F.L.; Suryanto, F.; Prasetiyadi, P.; Tilottama, R.D., (2025). Multi-dimensional perspectives on sustainability in domestic waste management. Global J. Environ. Sci. Manage., 11(2): 747-770.

DOI: 10.22034/gjesm.2025.02.21

URL: https://www.gjesm.net/article_722299.html

Global J. Environ. Sci. Manage. 11(2): 771-790, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

CASE STUDY

The impact of land use change on morphological and anatomical adaptations of Rhizophora species

A.B. Rangkuti[1,3,*], P. Peniwidiyanti[2], M. Basyuni[1,3], D. Elfiati[1,3], A. Susilowati[1,3], A. Mubaraq[1,4], M.R. Hariri[5], A.P. Dewi[5], F. Indriani[6], F.G. Dwiyanti[7], B. Slamet[1,3], K.S. Hartini [1,3], R.A. Syahputra[8]

[1] *Center of Excellence for Mangrove, Universitas Sumatera Utara, Medan, 20155, Indonesia*

[2] *Research Center for Ecology and Ethnobiology, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor, Cibinong, West Java, 16911, Indonesia*

[3] *Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Medan, 20155, Indonesia*

[4] *Doctoral Program of Agricultural Sciences, Faculty of Agriculture, Universitas Sumatera, Medan, 20155, Indonesia*

[5] *Research Center for Biosystematics and Evolution, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor, Cibinong, West Java, 16911, Indonesia*

[6] *Research Center for Applied Botany, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor, Cibinong, West Java, 16911, Indonesia*

[7] *Department of Silviculture, Faculty of Forestry and Environment, IPB University, Ulin Street, IPB Dramaga Campus, Bogor, West Java, 16680, Indonesia*

[8] *Department of Chemistry, Universitas Negeri Medan, Jl. Willem Iskandar, Pasar V, Medan Estate, Medan, 20221 Indonesia*

ARTICLE INFO

Article History:
Received 07 October 2024
Revised 13 December 2024
Accepted 16 January 2025

Keywords:
Anatomical
Mangrove
Morphological
Rhizophora spp

ABSTRACT

BACKGROUND AND OBJECTIVES: The ongoing destruction of mangrove forests highlights the urgent need for mitigation and control efforts. Indonesia, home to a rich diversity of mangrove species, has the potential to provide viable solutions to address this issue. The main objective of researchers is to maintain the existence of all species. It is crucial that research data support control and mitigation strategies to ensure efficient and optimal management of these ecosystems. Analyzing how a species responds to alterations in land use can yield significant understanding of its capacity for adaptation. The ability to adapt can be assessed by analyzing variations in leaf structure and anatomy. This study investigated the morphological and anatomical characteristics of three species in the *Rhizophora*ceae family: *Rhizophora mucronata*, *Rhizophora apiculata*, and *Rhizophora stylosa*, which thrive in three distinct mangrove ecosystems in North Sumatra Province. The purpose was to examine how effectively these species have modified their behaviors and characteristics in relation to shifts in their environmental conditions. This study sought sought to evaluate the extent to which these species have adjusted to the changing environmental conditions in their habitat located in North North Sumatra Province, Indonesia.
METHODS: This study aimed to select sites that illustrated three unique land uses residential areas in Belawan Sub-District, healthy mangrove forests in Sitardas Village, and mangrove areas designated for fish pond activities in Percut Sei Tuan Sub-District. Observations were made on three mangrove species: *Rhizophora apiculata* Blume, *Rhizophora mucronata* Poir, and *Rhizophora stylosa* Griff, to assess how their leaf morphology and anatomy respond to changes in land use within their natural environments. Leaf samples were collected from three separate locations, ensuring that ten trees of each species were included at each site. Each tree had five branches, and from each branch, five healthy leaves were selected for measurement and analysis. Data were gathered on 12 distinct characters. The method of stomatal printing was used to prepare leaf material for the analysis of stomatal characteristics. Data were collected on seven characteristics. Stomatal density and stomatal index were measured across 15 units per leaf. The morphological and anatomical characteristics of *Rhizophora apiculata*, *Rhizophora mucronata*, and *Rhizophora stylosa* were statistically analyzed using Analysis of Variance. Furthermore, a principal component analysis graphic was utilized to depict the environmental parameters, emphasizing the differences observed among the sampling locations.
FINDINGS: The results revealed that the varying land use conditions at each study site affected the three species of *Rhizophora*. *Rhizophora stylosa* was unable to grow at the Medan Belawan study site due to severe damage and pollution. In contrast, the other two sites, Percut Sei Tuan and Sitardas, are lightly polluted environments that are suitable for all three *Rhizophora* species. This finding demonstrates that certain *Rhizophora* species, specifically *Rhizophora apiculata* and *Rhizophora mucronata*, can thrive in habitat conditions and environmental factors that are unsuitable for *Rhizophora stylosa*. Furthermore, there were notable variations in the stomatal index among all three *Rhizophora* species. *Rhizophora apiculata* had a stomatal index of 19.69, *Rhizophora mucronata* had a value of 111.7, and *Rhizophora stylosa* had a value of 24.67. These variations may impact their efficiency in adapting to their respective environments.
CONCLUSION: This study offers insight into how three *Rhizophora* species adapt to changes in land use. Each species demonstrates distinct adaptations influenced by various factors. The outcomes of this study will be instrumental in suggesting species that can effectively contribute to restoration initiatives within mangrove ecosystems.

DOI: 10.22034/gjesm.2025.02.22

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
79

NUMBER OF FIGURES
5

NUMBER OF TABLES
4

*Corresponding Author:
Email: *baiqunirangkuti@usu.ac.id*
Phone: +6281318139274
ORCID: 0000-0002-3019-6038

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Indonesia is home to the largest mangrove forest area in the world, covering approximately 2.7 million hectares (Mha), which represents 22.6 percent (%) of the global mangrove forests as of 2020. Within this vast region, North Sumatra Province hosts around 57,010 hectares of mangrove forests (Basyuni *et al.,* 2022). The unique structural and functional characteristics of mangrove ecosystems contribute significantly to environmental health and support a diverse range of living organisms. These benefits include supporting essential ecological processes (Lee *et al.,* 2014; Primavera *et al.,* 2019; Mitra, 2020), providing important hydrological functions (Perez-Ceballos *et al.,* 2020; Adame *et al.,* 2021), creating habitats for diverse species (Wahyuni *et al.,* 2021; Badave *et al.,* 2023; Bindiya *et al.,* 2023), supplying food sources (Contreras *et al.,* 2018; Muro-Torres *et al.,* 2020), mitigating the impact of natural disasters (Asari *et al.,* 2021; Akram *et al.,* 2023), biogeochemical cycles including nitrogen that contribute to mitigating greenhouse gas emissions (Mubaraq *et al.,* 2024), and serving as potential areas for ecotourism (Azis *et al.,* 2018; Abdillah *et al.,* 2020). Remarkably, mangrove forests prosper in settings that are typically severe and challenging (Akram *et al.,* 2023). The organisms that inhabit these forests have adapted to cope with high salinity, strong wind, elevated temperature, anaerobic muddy soil (Koh *et al.,* 2018), and the frequent disturbances caused by tidal changes in seawater (Friess *et al.,* 2020). The global decline of mangrove ecosystems is occurring at an alarming pace, primarily due to intense human activities that exert significant pressure on these vital habitats. The pressures arise from several elements, including an increasing population, shifts in land use practices, and diverse sources of pollution caused by human activities (Ferreira and Lacerda, 2016; Carugati *et al.,* 2018; Bryan-Brown *et al.,* 2020). The Food and Agriculture Organization (FAO) reported that the total global mangrove area in 2020 is estimated at around 14.8 Mha. Between 1990 and 2020, there was a total loss of 1.04 million hectares, with the annual loss rate decreasing from 46,700 hectares per year during 1990–2000 to 21,200 hectares per year during 2010–2020 (FAO, 2020). As per the 2022 findings released by the Republic of Indonesia's Ministry of Environment and Forestry, 2.32 million hectares of the total 3.48 million hectares of mangrove land are deemed healthy, with a tree density surpassing 1,500 per hectare. In contrast, 1.16 million hectares are identified as damaged. Annually, around 200,000 hectares (ha) of mangroves are damaged in Indonesia, primarily due to land conversion for agriculture (Ilman *et al.,* 2016; Rahman *et al.,* 2020). Human activities and climate change are the primary drivers behind the degradation of coastal vegetation, including mangroves (Wang and Gu, 2021). Examples of human activities that negatively impact the landscape include land use changes, habitat loss, mangrove logging, industrial activities, the invasion of alien species, and the overexploitation of biological resources (Cahyaningsih *et al.,* 2022). Significant degradation is occurring in the mangrove forests of North Sumatra, primarily due to shifts in land use and land cover that often fail to take environmental factors into account. Study conducted by Bryan *et al.* (2013), Sasmito *et al.,* (2019), and Basyuni *et al.,* (2021) indicates that the mangrove forests in Percut Sei Tuan Sub-District, Deli Serdang Regency, as well as those studied in Medan Belawan Sub-District, Medan City, have experienced a significant decline over the past fourteen years. Through mapping and analyzing changes in mangrove forest cover using remote sensing, geographic information system (GIS), and analytical hierarchy process (AHP), one study concluded that prioritizing economic reasons is essential to halt further changes (Rahmawaty *et al.,* 2022). In contrast, the mangrove forest in Sitardas Village, located in Central Tapanuli, is well-preserved (Muhtadi *et al.,* 2020; Rangkuti *et al.,* 2024). Land-use activities play a significant role in climate change, and shifts in land-cover patterns are one of the ways the effects of climate change become evident. The relationship between land use and climate change encompasses the effects of modifications in land use on atmospheric carbon dioxide (CO2) concentrations, as well as the resulting implications for the climate system (Barati *et al.,* 2023). Climate change poses a significant threat to the survival of plants. Understanding plant anatomy and morphology offers valuable insights into their resilience, adaptation, resource efficiency, carbon dynamics, and ecosystem interactions. By examining the anatomy and morphology of plants, traits associated with tolerance to climate stress can be identified, which can help to better understand how plants adapt to changing conditions. Such knowledge can facilitate the conservation of at-risk

plant species and bolster breeding efforts designed to produce more robust plant variants, in addition to fostering sustainable management in an evolving ecological landscape. Although many studies have focused on how land use changes affect anatomy and morphology, there are still few references available on how these changes lead to environmental changes that influence the adaptation process, particularly concerning the morphological and anatomical characterizations of mangrove species. Therefore, this study examined the morphological and anatomical traits of three Rhizophoraceae species, namely *Rhizophora mucronata*, *R. apiculata*, and *R. stylosa,* growing in three distinct mangrove ecosystems in North Sumatra Province. The aim of the current study is to determine how well these species adapted to changing habitat environmental conditions. This study was carried out in North Sumatra Province, Indonesia, in 2023.

MATERIALS AND METHODS

Study area

This study was conducted from April to December 2023 in three mangrove ecosystem locations in North Sumatra Province, Indonesia. The study sites included Percut Sei Tuan Sub-District in Deli Serdang Regency, the Medan Belawan Sub-District in Medan City, and Sitardas Village in Central Tapanuli Regency (Fig. 1). Data collection and material observations were conducted over the course of the year. Nevertheless, the consistent and stable nature of air temperature and humidity in tropical regions ensured that these factors did not compromise the accuracy of the data gathered (Noer *et al.,* 2022). The mangrove ecosystems in Percut Sei Tuan and Medan Belawan Sub-Districts represent mangrove ecosystems that have been degraded (Fig. 2a and 2b), while the mangrove ecosystem in Sitardas Village represents a mangrove ecosystem that is still well-preserved

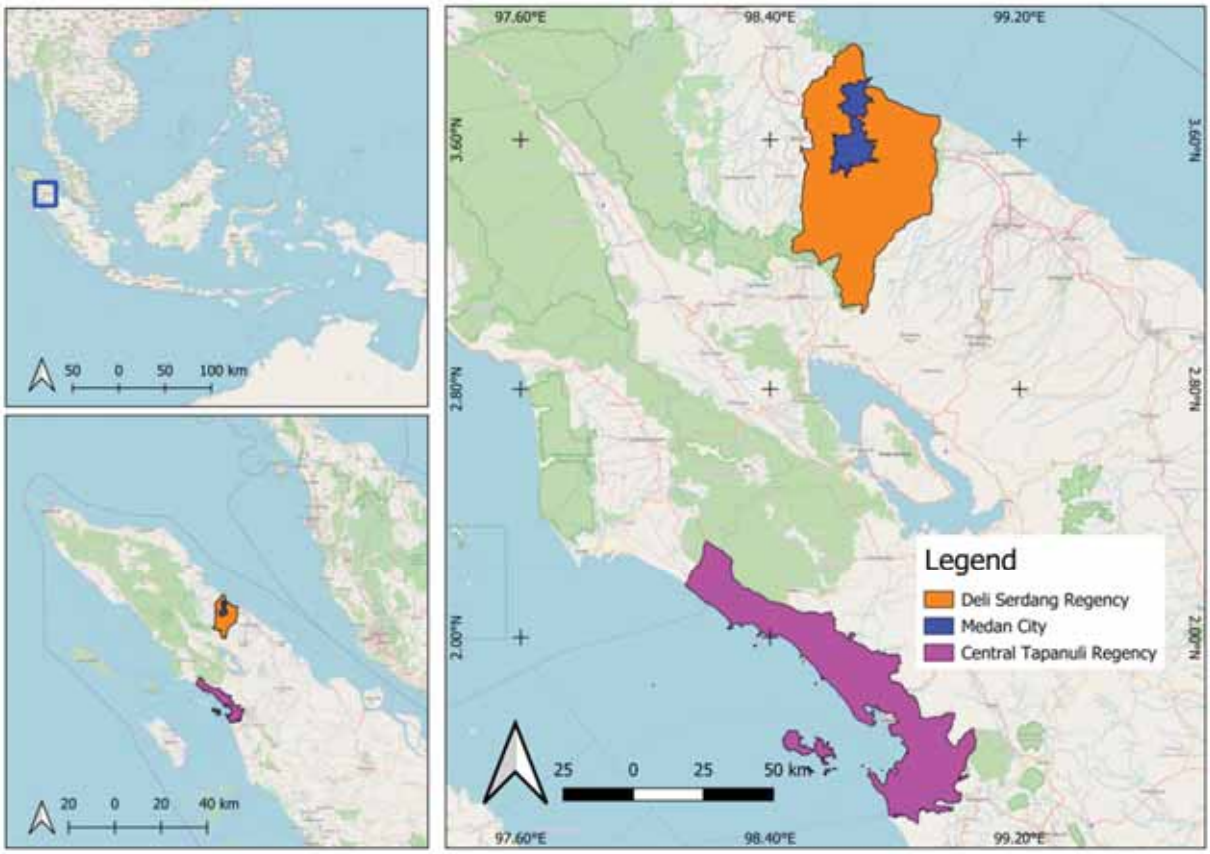


Fig. 1: Geographical location of the study area in Deli Serdang Regency, Medan City, and Central Tapanuli Regency in North Sumatra Province, Indonesia

(Fig. 2c). As of 2016, the alteration of mangrove ecosystems for different land purposes in the Percut Sei Tuan Sub-District had resulted in over 80% of these ecosystems being identified as facing moderate to high degrees of degradation (Sulistiyono *et al.,* 2019). These areas predominantly have a substrate of sandy mud (Hasibuan *et al.,* 2021). The most severe damage to mangrove ecosystems occurred in the Medan Belawan Sub-District of Medan City, which was characterized by roily seawater and elevated nitrate and phosphate levels exceeding water quality standards (Widiani *et al.,* 2021). This implies that the aquatic environments and ecosystems in the Medan Belawan Sub-District are suffering from pollution caused by human actions, including the disposal of waste, domestic refuse, and oil spills from the port of Belawan port (Harefa *et al.,* 2022). Generally, the substrate around the Medan Belawan Sub-District



Fig. 2: Overview of the study site at the three locations: a. Percut Sei Tuan, b. Medan Belawan, and c. Sitardas

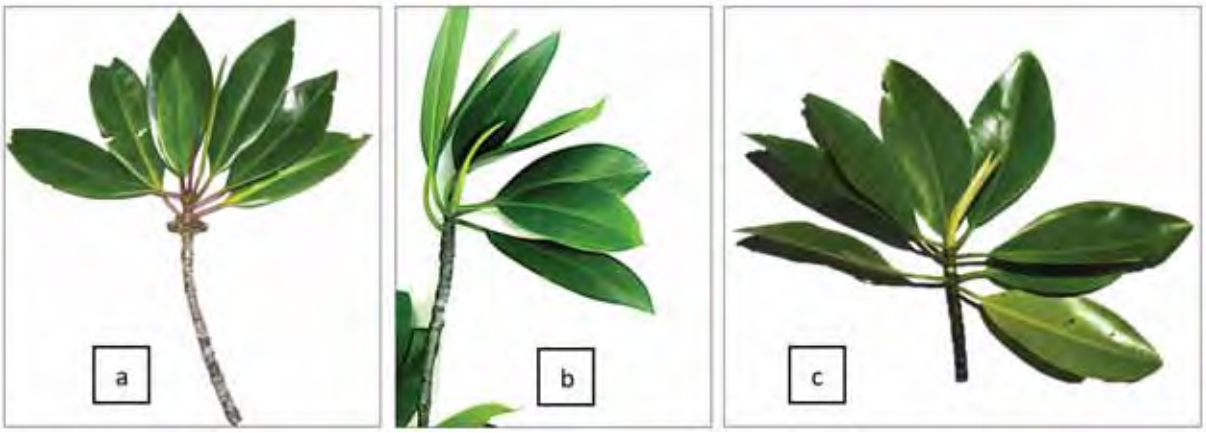


Fig. 3: Leaves sample of *Rhizophora apiculata* (a), *R. mucronata* (b), and *R. stylosa* (c).

consists of muddy clay, which contributes to a higher abundance of microplastics in mangrove sediments compared to the water flow in estuaries (Leidonald *et al.,* 2024). In contrast, the mangrove ecosystem in Sitardas Village is distinguished by a substrate that is predominantly made up of sandy soil, coral fragments, and patches of sandy mud. This ecosystem is also found adjacent to seagrass and coral reef ecosystems, which remain in good condition to this day (Muhtadi *et al.,* 2020).

Data collections

In this study, the morphology and anatomy of the leaves of three commonly found mangrove species in the Indo-Malayan region, namely R*hizophora apiculata* Blume, *R. mucronata* Poir, and *R. stylosa* Griff (Setyawan *et al.,* 2014), were observed in order to understand how these species adapt to changes in land use in their habitat (Fig. 3).

A targeted sampling method was employed to collect leaf twigs for the analysis of their morphological and stomatal characteristics. The collected leaf twigs were in healthy and intact conditions (Baroga and Buot, 2014). Data were gathered on 12 distinct characters, which included 7 qualitative and 5 quantitative characters. The observed qualitative traits encompassed the shape of the leaves, the coloration of both the upper and lower surfaces, the types of leaf tips and bases, the nature of the leaf edges, and the type of leaf reinforcement. Meanwhile, the quantitative characteristics measured consisted of stipule length (SL), lamina length (LL), leaf width (LW), petiole length (PL), and leaf point (LP). The color of the adaxial and abaxial of *Rhizophora* spp. Leaves were characterized using the Mussell Chart. A total of 50 leaf twigs from each species were observed and measured, with five twigs collected from ten trees for each species. To observe stomatal characteristics, the leaf material was prepared using the stomatal printing technique (Purnomo *et al.,* 2023). The procedure begins with selecting mature leaves from each species studied. Transparent nail polish is then applied to the upper surface of the leaf (adaxial side). Once the nail polish had dried, transparent tape was applied over it. The sample was then carefully placed onto the prepared glass. The printed epidermal layer is subsequently observed using an Olympus CX23 digital microscope connected to an Otilab camera and a computer screen. Data was gathered based on seven distinct characteristics, comprising three qualitative and four quantitative characters. The qualitative characteristics observed included stomata type, epidermis shape, and anticlinal wall type. Furthermore, the quantitative characteristics observed were: 1) The number of stomata in the field of view. 2) The length and width of stomata. 3) The number of epidermises in the field of view. Stomatal density and stomatal index were observed in 15 units per leaf. Each unit leaf area was observed under a microscope with 20x magnification and in a field of view measuring 382,900 micrometers (µm) x 722,285 µm. Additionally, the length and width of stomata were observed on 25 stomata with 40x magnification in a field of view measuring 355,674 µm x 188,420

µm. The methodology established by Dilcher (1974) was utilized to identify the characteristics of stomata.

Data analysis

A descriptive analysis of stomatal density and index was conducted, utilizing both qualitative and quantitative observations. Calculations of stomatal density and stomatal index values were analyzed using Eqs. 1 and 2 (Paul *et al.*, 2017):

$$\text{Stomatal density} = \frac{Number\ of\ stomata}{Field\ of\ view under\ microscope} \quad (1)$$

$$\text{Stomatal index} = \frac{Number\ of\ stomata}{Number\ of\ stomata + number\ of\ epidermal\ cells} \times 100\% \quad (2)$$

Statistical analysis

The morphological and anatomical characteristics of *R. apiculata*, *R. mucronata*, and *R. stylosa* were statistically analyzed using analysis of variance (ANOVA). Following the identification of statistically significant differences in the ANOVA results, additional analysis was conducted utilizing the Tukey test for post-hoc comparisons. This approach helped to identify significant differences among *R. apiculata*, *R. mucronata*, and *R. stylosa* collected from Percut Sei Tuan, Medan Belawan, and Sitardas. This analysis took into account various environmental factors including wind speed (meter per second (m/s)), light intensity (lux), humidity (%), temperature in degrees Celsius (°C), potential of hydrogen (pH), total dissolved solids (TDS), parts per million (ppm), electrical conductivity (EC), milisiemens per centimeter (mS/cm), and salinity (ppm), all of which may influence mangrove growth. These parameters were subsequently depicted in a principal component analysis (PCA) graphic to demonstrate the differences among the study locations: Percut Sei Tuan, Medan Belawan, and Sitardas. All analyses were conducted using paleontological statistics (PAST) 4.17 software (Hammer and Harper, 2024).

RESULTS AND DISCUSSION

Environmental factors affecting the mangrove ecosystem

The PCA graphic presented in this study illustrates the variance within a dataset. The x-axis (PC1) accounts for 79.28% of the variance, while the y-axis (PC2) represents 12.16%. Nearly all the variability in the dataset can be attributed to these two components, which makes them particularly suitable for comprehending and analyzing data trends. The data points are classified into three groups: Percut Sei Tuan, Medan Belawan, and Sitardas. The representation of each group is distinct, with dots for Percut Sei Tuan, squares for Medan Belawan, and diamonds for Sitardas (Fig. 4).

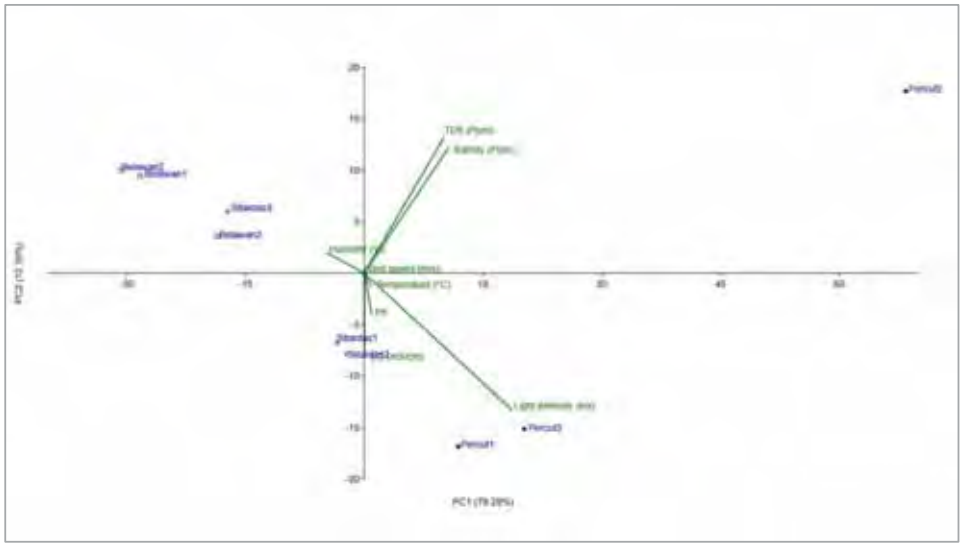


Fig. 4: Principal component analysis for three study sites

The distribution of points revealed significant differences between the various group locations. The Percut Sei Tuan data, particularly along PC1, display notable variation, with Percut-2 positioned far to the right. This indicates a specific profile in the dataset, showcasing an additional type of uniqueness when compared to the other locations. In contrast, the Belawan and Sitardas locations cluster closely to the origin, which signifies that these groups are more similar to each other and exhibit limited variance along both PC1 and PC2. The differentiation between the groups reveals important variations in their core attributes. The environmental elements in the Percut Sei Tuan group appear to be more diverse, while the environmental factors in the Medan Belawan and Sitardas groups are more uniform. Percut-2 may reflect significant variability in environmental factors due to its remote position on the plot, highlighting distinctive features not observed in other locations. The results of the PCA highlight evident groupings and illustrate that the first principal component is responsible for the largest portion of variance in the dataset, positioning it as the key axis for interpreting differences across the locations. The dataset presents an analysis of environmental parameters across three locations: Percut Sei Tuan, Medan Belawan, and Sitardas, highlighting distinct variations among the sites. Wind speed ranged from 0.53 m/s in Medan Belawan to 2.44 m/s in Sitardas, with Sitardas consistently exhibiting higher values. Light intensity demonstrated substantial variability, peaking at 86.33 lux in Percut Sei Tuan and reaching its lowest point at 11.27 lux in Medan Belawan, indicating that Medan Belawan generally experienced reduced light exposure. Sitardas experienced the highest humidity levels at 77.00%, in contrast to Percut Sei Tuan, which had the lowest at 56.20%. Throughout the observations, Sitardas consistently exhibited greater relative humidity throughout the measurements. Temperature measurements showed limited fluctuation, ranging from 30.04°C in Medan Belawan to 33.96°C in Percut Sei Tuan, with Percut Sei Tuan displaying slightly elevated temperatures compared to the other sites. The pH levels varied within a neutral to slightly alkaline range, with the highest value of 20.70 observed in Percut Sei Tuan and the lowest at 6.65 in Medan Belawan. There was notable variation in total dissolved solids (TDS), with the maximum concentration found in Percut Sei Tuan at 54.67 ppm and the minimum in Sitardas at 10.00 ppm, highlighting the increased variability in Percut Sei Tuan. Similarly, Electrical Conductivity (EC) was highest in Percut Sei Tuan (34.40 mS/cm) and lowest in Sitardas (10.64 mS/cm). Salinity ranged from 11.70 ppm in Medan Belawan to 58.29 ppm in Percut Sei Tuan, highlighting significantly elevated salinity in Percut Sei Tuan.

Morphological characteristics of R. apiculata, R. mucronata, and R. stylosa

Field observations conducted in three study sites revealed that *Rhizophora apiculata* and *R. mucronata* naturally grow in Percut Sei Tuan, Medan Belawan, and Sitardas, while *R. stylosa* is only found in Percut Sei Tuan and Sitardas. This distribution could be linked to the compromised and polluted state of the mangrove environment ecology in Medan Belawan. *Rhizophora apiculata* and *R. mucronata* thrive in intertidal mangrove environments characterized by muddy substrates and tidal influences, demonstrating adaptations to high salinity levels and harsh environmental conditions (Shamin-Shazwan *et al.,* 2021). Conversely, *R. stylosa* is usually situated in coastal mangrove habitats and is often subject to (Chen and Wang, 2017). Both *R. apiculata* and. *R. mucronata* are common mangrove species found in various regions of Indonesia and are extensively utilized by local communities. These species assist in the preservation of embankments, and their wood is valuable for making fish traps and providing firewood. Furthermore, they are distinguished by their high levels of total tannins (Setyawan *et al.,* 2019; Hilmi *et al.,* 2021). These two mangrove species often grow together, making it difficult for the community to distinguish between them due to their similar morphological characteristics (Shamin-Shazwan *et al.,* 2021). It is intriguing that both species can create natural hybrids in their respective (Ng and Chan, 2012). In this study, the three *Rhizophora* species observed showed overall similarities in leaf morphology, particularly in terms of margin and venation. Specifically, *R. apiculata* and *R. mucronata* exhibited similarities in leaf apex and base, while *R. apiculata* and *R. stylosa* shared similarities in leaf shape and color (Table 1).

The effects of land-use changes on the quantitative morphological characteristics of three *Rhizophora* species: *R. apiculata*, *R. mucronata*, and *R. stylosa,*

Table 1: Qualitative leaf morphology of *Rhizophora* spp.

Species	Shape	Adaxial colour	Abaxial colour	Apex	Base	Margin	Venation
R. apiculata Blume	Elliptic	2.5 GY 6/6	5.0 GY 7/6	Cuneate	Convex	Entire	Pinnate
R. mucronata Poir.	Oblong	10.0 GY 6/10	2.5 GY 7/8	Cuneate	Convex	Entire	Pinnate
R. stylosa Griff.	Elliptic	10.0 GY 5/8	5.0 GY 7/8	Convex	Rounded	Entire	Pinnate

Table 2. Quantitative leaf morphology of *Rhizophora* spp.

Location	SL	LL (cm)	LW (cm)	PL (cm)	LP (cm)
Rhizophora apiculata Blume					
Medan Belawan	5.49±1.38^{a}	14.29±2.02^{a}	5.03±1.04^{a}	2.16±0.55^{b}	6.62±1.13^{a}
Percut Sei Tuan	4.79±0.90^{a}	13.31±1.49^{a}	4.35±0.60^{a}	1.59±0.38^{a}	5.78±0.79^{a}
Sitardas	5.31±1.08^{a}	13.27±1.45^{a}	5.45±0.78^{b}	2.40±0.84^{b}	6.21±0.73^{a}
Rhizophora mucronata Poir					
Medan Belawan	6.49±1.23^{b}	17.07±2.39^{b}	9.04±1.58^{b}	3.15±0.65^{b}	7.84±1.25^{b}
Percut Sei Tuan	5.34±1.22^{a}	10.46±2.51^{a}	5.88±1.04^{a}	2.24±0.59^{a}	2.64±0.91^{a}
Sitardas	6.00±1.46^{a}	15.45±2.18^{b}	8.32±1.30^{b}	3.04±0.58^{b}	7.76±1.23^{b}
Rhizophora stylosa Griff					
Percut Sei Tuan	5.58±0.97^{a}	10.33±1.27^{a}	5.39±0.77^{a}	2.65±0.50^{a}	4.96±0.73^{a}
Sitardas	5.45±0.75^{a}	12.84±1.70^{b}	5.18±0.86^{a}	2.14±0.45^{b}	6.29±0.92^{b}

Note: SL = Stipule Length; cm = centimeter; LL = Lamina Length; LW = Leaves Width; PL = Petiol Length; LP = Leaves Point.
Different notations indicate significant differences between groups based on post hoc analysis ($p < 0.05$).

are detailed in Table 2. An analysis using the post hoc Tukey method on leaf morphological features, namely stipule length (SL), leaf length (LL), leaf width (LW), petiole length (PL), and leaf point (LP), demonstrates significant variations in these characteristics across diverse locations and species.

Feng *et al.* (2016) discovered that water stress can diminish leaf size by inhibiting cell division and expansion. In the present study on *R. apiculata*, it was found that stipule length (F=1.092) and lamina length (F=0.7907) were not significantly affected by habitat conditions. It was found that leaf width experienced a significant impact (F=10.31), petiole length had a moderate influence (F=8.647), and the leaf point was affected to a lesser extent (F=3.131). Notably, the Sitardas population exhibited a significant leaf width (LW: 5.45 ± 0.78 cm) compared to the Medan Belawan and Percut Sei Tuan populations. In comparison, petiole length was significantly longer in Medan Belawan (PL: 2.16 ± 0.55 cm) and Sitardas (PL: 2.40 ± 0.84 cm) populations than in the Percut Sei Tuan population (PL: 1.59 ± 0.38 cm). The diversity in leaf width of *R. apiculata* highlights the importance of habitat conditions in its growth, as these plants adapt their morphology to improve photosynthesis, light absorption, and evapotranspiration (Tamimi *et al.*, 2021). In the present study on *R. mucronata*, stipule length is only weakly affected (F=5.693), whereas lamina length (F=45.43), leaf width (F=34.04), and leaf point (F=24.64) were strongly affected. While most characters displayed considerable differences, petiole length in the Medan Belawan and Sitardas populations remained an exception, as it was significantly elevated compared to that in the Percut Sei Tuan population. Belawan displayed the highest values for stipule length (SL: 6.49 ± 1.23 cm), lamina length (LL: 17.07 ± 2.39 cm), leaf width (LW: 9.04 ± 1.58 cm), and leaf point (LP: 7.84 ± 1.25 cm), while Percut Sei Tuan consistently recorded the lowest values, particularly for leaf point (LP: 2.64 ± 0.91 cmAdditionally, recent findings reveal that *R. mucronata* leaves can function as bioindicators for high copper concentrations, with a noticeable decrease in average leaf area corresponding to increased copper levels (Perez *et al.*, 2021). *Rhizophora stylosa* is primarily found in seaside mangrove forests and is often subjected to tidal inundation. This species demonstrates a strong ability to compete and thrive in ecosystems with high salinity and prolonged inundation periods (Chen and Wang, 2017; Chen *et al.*, 2022). Findings from the statistical analysis demonstrated that there are only minor morphological changes in

response to differing ecosystem conditions. Notably, lamina length (F=28.68) and leaf point (F=24.71) are strongly affected, while stipule length is weakly affected (F=2.81), petiole length is moderately affected (F=9.979), and leaf width showed no significant impact (F=0.6409). Significant differences were identified in lamina length and petiole length between Percut Sei Tuan and Sitardas, with the Sitardas recording a longer lamina length (LL: 12.84 ± 1.70 cm) and Percut Sei Tuan a greater petiole length (PL: 2.65 ± 0.50 cm). However, no significant differences were found in SL, LW, or LP between the two locations, as indicated by the shared notation "a." The differences in leaf structure can be linked to the diverse environmental conditions that each species experiences in its specific habitats. For instance, *R. mucronata* showed greater morphological plasticity, which may enhance its adaptability to changing environmental conditions (Fox *et al.,* 2019). Adaptability plays a key role in the survival of species within dynamic coastal ecosystems, where human activities can lead to significant fluctuations in factors such as salinity, nutrient availability, and hydrology (Cloern *et al.,* 2016). Moreover, the distinct differences in leaf features among the species imply that each has undergone evolutionary changes that enable them to maximize resource efficiency in their particular habitats. For example, variations in leaf width and length can influence photosynthetic efficiency and water retention, which are vital for survival in mangrove habitats (Iqbal *et al.,* 2024; Qie *et al.,* 2024). The ability of these species to adjust their morphology in response to land-use changes highlights the importance of considering species-specific characteristics in conservation and restoration efforts. Additionally, the effects of these morphological transformations go beyond individual species and impact the overall ecosystem. Mangroves are vital for safeguarding coastlines, capturing carbon, and offering habitats for numerous marine organisms. Therefore, changes in the morphological characteristics of *Rhizophora* species can affect their overall health and functionality, potentially leading to shifts in ecosystem services provided by mangrove forests (Sanchez *et al.,* 2021; Inoue *et al.,* 2024). Changes in leaf area or modifications in leaf structure may lead to a decline in the photosynthetic potential of these trees, impacting their growth rates and ability to sequester carbon, both of which play a vital role in climate change mitigation.

Anatomical characteristics of R. apiculata, *R. mucronata*, and *R. stylosa*

An evaluation of the anatomical characteristics of the leaves from *R. apiculata*, *R. mucronata*, and *R. stylosa* revealed that variations in land use can influence leaf anatomy, including differences in stomatal type, stomatal density, stomatal index, and stomatal length. The differences in leaf anatomical characteristics found among three distinct mangrove locations demonstrate that leaf anatomy is notably affected by environmental variations. The findings of this study demonstrate that there is substantial variation in the stomatal shape of *Rhizophora* species across the three sites examined. The stomata in *R. apiculata* and *R. stylosa* primarily exhibit an anomocytic type, with undulating or undulating to rounded anticlinal margins in *R. apiculata* and rounded anticlinal margins in *R. stylosa* (Table 3). Conversely, *R. mucronata* mainly shows the desmocyctic, paracytic, and pericytic types, which feature rounded anticlinal margins; however, the anomocytic type is also observed (Table 3). Several types of stomata found in the studied *Rhizophora* species are presented in Fig. 5. The structure of the anticlinal stomata plays a vital role in maintaining both structural and physiological functions of stomata, allowing them to operate effectively under various environmental conditions. Additionally, there is considerable variation in the shape of epidermal cells among three *Rhizophora* species observed at three distinct study sites (Table 3).

In the present study, the results of post-hoc analyses describe the stomatal characteristics of three *Rhizophora* species (*R. apiculata*, *R. mucronata*, and *R. stylosa*) across different locations in Medan Belawan, Percut Sei Tuan, and Sitardas (Table 4). The data includes the value of stomatal density (stomata per square millimeter), stomatal index (percentage), stomatal length (in micrometers), and stomatal width (in micrometers). Accompanying each value is its standard deviation, while letters signify the significant differences observed among the means values for each species. A prior study emphasized that that salinity stress significantly impacts stomatal density as an anatomical characteristic (Kiani-Pouya *et al.,* 2020; Ibrahim *et al.,* 2021; Chen *et al.,* 2022). In high salinity conditions, plants exhibit a reduction in

Table 3: Qualitative stomatal characteristics of *Rhizophora* spp.

Location	Type of stomatal	Epidermis cell shape	Type of anticlinal
Rhizophora apiculata			
Medan Belawan	Anisocytic Anomocytic* Brachyparatetracytic	Pentagonal Hexagonal	Undulate
Percut Sei Tuan	Anomocytic*	Pentagonal Hexagonal	Undulate to rounded
Sitardas	Anisocytic Anomocytic* Anomotetracytic	Pentagonal Hexagonal Square	Undulate to rounded
Rhizophora mucronata			
Medan Belawan	Anomotetracytic Desmocyctic* Paracyctic	Oval Square Pentagonal	Rounded
Percut Sei Tuan	Anisocytic Anomocytic Anomotetracytic Paracytic*	Square Pentagonal	Rounded
Sitardas	Anomocytic Paracytic Pericytic*	Oval Square	Rounded
Rhizophora stylosa			
Percut Sei Tuan	Anomocytic* Anomotetracytic Staurocytic	Square Pentagonal Hexagonal	Rounded
Sitardas	Anomocytic* Anomotetracytic Anisocytic Desmocyctic	Square Pentagonal Hexagonal	Rounded

Note: *dominant

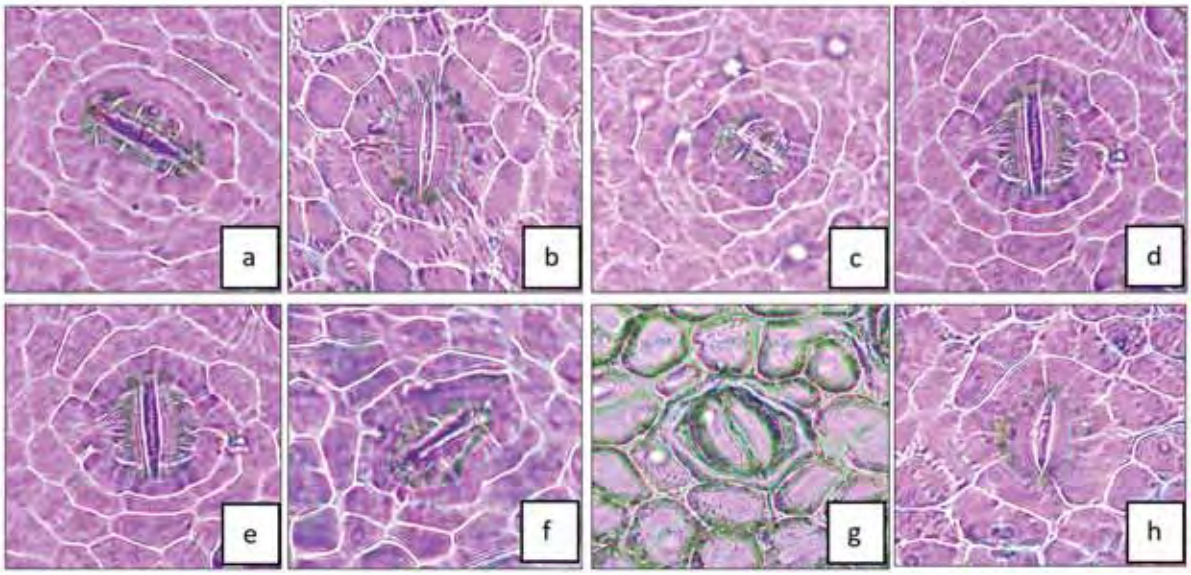


Fig. 5: Stomatal type. a. Anisocytic; b. Anomocytic; c. Anomotetracytic; d. Brachyparatetracytic; e. Desmocyctic; f. Paracytic; g. Pericytic; and h. Staurocytic.

Table 4: Quantitative stomatal characteristics of *Rhizophora* spp.

Location	Stomatal density (stomata/ milimeter (mm^2)	Stomatal index (%)	Stomatal length (µm)	Stomatal width (µm)
Rhizophora apiculata Blume				
Medan Belawan	109±7[a]	3.956±0.463[a]	55.50±6.99[a]	45.29±7.39[a]
Percut Sei Tuan	108±11[a]	3.035±0.344[c]	40.91±3.96[c]	27.57±5.25[c]
Sitardas	103±11[a]	3.456±0.393[b]	44.92±3.64[b]	36.93±7.75[b]
Rhizophora mucronata Poir				
Medan Belawan	101±11[a]	8.173±0.858[a]	64.29±6.06[a]	49.72±5.32[a]
Percut Sei Tuan	100±9[a]	4.832±0.759[b]	52.07±3.76[b]	38.27±2.95[b]
Sitardas	86±7[b]	4.644±0.525[b]	50.71±3.81[c]	39.85±3.42[b]
Rhizophora stylosa Griff				
Percut Sei Tuan	97±13[a]	4.062±0.788[a]	52.16±4.67[a]	40.04±2.74[a]
Sitardas	109±9[b]	2.907±0.225[b]	48.54±4.24[a]	36.06±4.83[b]

Different notations indicate significant differences between groups based on post hoc analysis ($p < 0.05$).

stomatal density, responding by improving water use efficiency without greatly affecting overall yield (Chen *et al.,* 2022). According to the salinity level observed at the study sites, Percut Sei Tuan has the highest salinity, averaging 33.06 ppm, while Medan Belawan and Sitardas have salinity levels of 12.67 ppm and 13.36 ppm, respectively. In this study, the trend of lower stomata density is found only in *R. stylosa*, which shows the stomatal density in the Percut Sei Tuan area is lower than in Sitardas with medium effects (F=8.612). Meanwhile, *R. apiculata* and *R. mucronata* show contradictive results (Percut Sei Tuan has a lower stomatal density than Medan Belawan but has a higher density than Sitardas) with no significant difference (F=1.489) and medium effect (F=12.61), respectively. As a combined residential and harbor zone, Medan Belawan is particularly susceptible to pollution, primarily because of the substantial quantity of chemical waste produced by households. Meanwhile, Percut Sei Tuan is the fish pond area threatened by logging and clearing mangrove areas for opening the fish pond. Furthermore, the similar stomatal density of *R. apiculate* indicated a level of consistency in this characteristic, even with changes in habitat conditions. The quantity of stomata is impacted by the level of pollution found in the mangrove ecosystem. Higher salinity levels can cause a decreased number of stomata (Samiyarsih *et al.,* 2016; Ulfaturrohmah *et al.,* 2024). The findings of this study indicated a relationship between the quantity of stomata and the stomatal index. Results indicated that *R. apiculata* and *R. mucronata* exhibited the lowest stomatal indices in Percut Sei Tuan, while *R. stylosa* had the highest. A comparable trend was noted across the species, indicating that the stomatal indices at Medan Belawan surpassed those recorded at Sitardas. Statistical analysis revealed a significant difference in the stomatal index of *R. apiculata* (F=19.69), indicating that this species is highly responsive to its growing environment. This capacity for adaptability could bolster the survival of R. apiculata amid changing conditions, yet it emphasizes the critical need to monitor environmental elements that may affect its growth. In contrast, *R. mucronata* demonstrated a greater sensitivity to anatomical changes, as evidenced by the strong effects on the stomatal index (F=111.7). This increased sensitivity suggests that *R. mucronata* may be more vulnerable to environmental stressors, which could affect its overall health and functionality in mangrove ecosystems. The ability of *R. mucronata* to respond to changes in its environment may be linked to its ecological role, as it often occupies areas with varying salinity and nutrient levels (Greaver *et al.,* 2016; Alongi, 2018). In addition, *R. stylosa* also exhibited a significant impact on its stomatal index (F=24.67), along with a medium effect on stomatal density and stomatal width. Despite these changes, *R. stylosa* demonstrated greater resilience to land-use changes compared to *R. apiculata* and *R. mucronata* in both Percut Sei Tuan and Sitardas. The ability to retain functional characteristics that aid in survival under changing conditions contributes to this resilience, playing a vital role in the maintenance of mangrove ecosystems (Srikanth *et al.,* 2016; Quadros *et al.,* 2021). The various land uses also influence

the stomatal size, both in length and width (Table 4). Rodriguez *et al.* (2018) explained that the response of stomatal adaptation (in terms of stomatal density and size) to cross-growing area conditions depends on each species. Smaller stomata confer mechanical advantages that improve the operational efficiency of guard cells. When the stomata are smaller, the turgor pressure from epidermal cells required to open the guard cells is also reduced, which in turn minimizes energy requirements. In this study, the stomatal length of *R. apiculata* showed a significant effect (F=26.19), along with its stomatal width. Similar findings were observed in *R. mucronate*, where the stomatal length (F=36.98), and stomatal width (F=27.34) also exhibited strong effects. The notable variations in stomatal length and width observed in both *R. apiculata* and *R. mucronata* suggest a pronounced sensitivity to morphological and anatomical changes resulting from alterations in their environmental growth conditions. Conversely, in *R. stylosa*, the stomatal width (F=10.42) exhibited medium effects, while the stomatal length showed weak effects (F=2.63). Comprehending these responses is vital for creating successful conservation and management strategies, particularly in the context of ongoing changes in land use and climate variability. The diverse reactions of these species to environmental shifts underscore the necessity of implementing species-specific management strategies in restoration and conservation initiatives, ensuring that the distinct adaptations of each species are considered.

Previous findings indicate that *R. stylosa* possesses superior anatomical features, suggesting that it has a good tolerance to both salinity and pollution conditions. The absence of *R. stylosa* in Medan Belawan is particularly noteworthy, given the species' known adaptability to varying salinity levels and polluted environments. This absence brings to light critical ecological issues concerning the interplay between environmental conditions and the distribution of species. The growth and establishment of *R. stylosa* are strongly influenced by several factors, including habitat characteristics, the broader ecosystem dynamics, and the specific properties of the substrate. Notably, *R. stylosa* has been reported to thrive on sandy substrates and coral beds, as highlighted by Kalasuba *et al.* (2023). The absence of this species in Medan Belawan could suggest that there are limiting factors associated with substrate composition or ecosystem conditions that prevent its establishment, even though it is highly adaptable. Delving deeper into these environmental and ecological aspects could enhance our comprehension of the determinants affecting the distribution of *R. stylosa*.

Conservation and restoration of mangrove ecosystem

The morphology and stomatal structure of three *Rhizophora* species have been significantly influenced by alterations in land use. Among these, *Rhizophora mucronata* displayed the greatest sensitivity to these changes, while *R. stylosa* showed higher resistance. The alterations in stomatal characteristics, such as the stomatal index, length, and width, highlighted the ways in which these species adjust to varying environmental conditions. It is important to consider appropriate conservation policies based on the sensitivity of each species to land use change in their respective habitats. Overall, the findings of this study provide valuable insights into the different environmental factors influence the stomatal morphology and characteristics of *Rhizophora* species. These insight can lead to the formulation of more impactful conservation strategies for coastal zones and mangrove forests. By analyzing the specific characteristics of each species alongside the health of their ecosystems, multiple conservation and restoration strategies can be recommended.

Ecological characteristics and conservation practiced

On Sumatra Island, there are 171 species of mangrove, of which 38 are classified as true mangroves, primarily represented by *R. mucronata* and *R. apiculata* (Rahman *et al.,* 2024). *Rhizophora* spp. is part of the true mangrove category and is found in the second layer of the zonation of the mangrove ecosystem. The outermost layer consists of *Avicennia* spp. and *Sonneratia* spp., which thrive in flooded conditions, while *Rhizophora* spp. occupies the next layer, located in areas that are inundated during high tides. *Rhizophora's* adaptation mechanism has proven effective in enduring a range of inundation conditions and various types of substrates. Ecologically, the three *Rhizophora* species found in Indonesia prefer similar growth habitats, although their tolerance to specific limiting factors varies slightly. Mangrove species are impacted by

three primary tolerance limits: the characteristics of the soil, the salinity of the environment, and their resilience against currents and surf conditions. T the ability to germinate, as well as the level of resistance and adaptation to environmental changes, differs among species. Certain species are restricted by their particular environmental requirements (stenocous), while those that possess a greater tolerance (eurycous) experience fewer challenges in their growth and development. For example, *R. mucronata* is sterile when growing in highly saline sea environments; however, it regularly produces fruit when growing along sedimentary stream banks. *Rhizophora apiculata* has growth preferences similar to those of *R. mucronate* but has a lower tolerance for environmental variations. In contrast, *R. stylosa* exhibits accelerated growth at moderate salinity levels (Inoue *et al.,* 2024).

a. Restoration practiced

Numerous studies have reviewed the restoration efforts of the mangrove ecosystem in Indonesia (Gerona-Daga and Salmo, 2022). A comprehensive assessment of mangrove restoration initiatives in Medan Belawan and Percut Sei Tuan has been performed, accompanied by ongoing progress monitoring (Hanggara *et al.,* 2021). However, collaborative efforts to ensure the recovery and sustainability of mangrove ecosystems in Medan Belawan and Percut Sei Tuan must continue, including preserving mangrove ecosystems around Sitardas and surrounding islands. To promote ecosystem recovery and shield the coastline from erosion and other environmental impacts, it is vital to implement planting initiatives that include true mangrove species in addition to *Rhizophora* spp. Facilitating the natural regeneration of mangrove vegetation necessitates an extended period and the management of multiple internal and external challenges that may hinder germination, growth, and development processes. Restoration practices for mangrove ecosystems are critical for enhancing their resilience and functionality, particularly considering the physiological variations observed among species such as *R. apiculata*, *R. mucronata*, and *R. stylosa*. The information regarding stomatal characteristics, such as density, index, length, and width, highlights the importance of choosing suitable species and comprehending their unique adaptations to local environmental conditions in restoration initiatives. For instance, *R. mucronata*, which exhibits a higher stomatal index and density under optimal conditions, may be prioritized in restoration projects aimed at improving carbon sequestration and habitat provision (Lovelock *et al.,* 2022). Additionally, the inclusion of a wide range of species can bolster biodiversity and enhance ecosystem resilience, given that various species respond differently to environmental challenges (Murray *et al.,* 2018). Effective restoration strategies must also consider the hydrological and sedimentary dynamics of the site, as these factors significantly influence the growth and survival of mangrove species (Krauss *et al.,* 2016). Incorporating these insights into restoration efforts can enhance the resilience of mangrove ecosystems, enabling them to better endure the effects of climate change and anthropogenic activities. Habitat restoration techniques, pollution control, salinity management, ongoing monitoring, community education, and technology adoption are essential strategies for managing the mangrove ecosystem, particularly those involving *Rhizophora* species adaptation. These strategies contribute to the sustainability of *Rhizophora* species while simultaneously enhancing the health and functionality of mangrove ecosystems, which in turn makes them better equipped to adapt to changing environmental circumstances. This study advocates for the use of wild species in restoration efforts. Specifically, the ability of *R. mucronata* and *R. apiculata* to adapt to changes in land use makes them highly recommended for it improving the success of habitat restoration initiatives.

b. Environmental impacts of mangrove conservation on society

The conservation of mangrove ecosystems yields a range of benefits and effects for both the ecological landscape and the communities that inhabit the area. Multiple reviews of conservation efforts in Southeast Asia have recommended practical approaches, including designating mangrove areas as marine protected areas, promoting collaborative management among stakeholders, encouraging private sector involvement in management and protection, and implementing payment for ecosystem services (PES) mechanisms (Friess *et al.,* 2016). The urgent restoration of mangrove ecosystems in Medan Belawan is crucial for assisting local residents in

managing the tidal flooding that regularly impacts the area (Sarveleni *et al.,* 2023). Compared to other study sites, Medan Belawan requires more comprehensive management from various parties due to the significant land use changes that occurred between 2005 and 2019, which have resulted in considerable mangrove habitat destruction and negatively impacted the surrounding ecosystem (Rahmawaty *et al.,* 2023). Alterations in land use surrounding mangrove ecosystems, including the transformation into ponds or residential developments, can significantly impact the long-term viability of species such as *Rhizophora* spp. The consequences of these changes include the loss of habitat for mangrove flora and fauna, habitat fragmentation, changes in forest structure, and changes in hydrology. Nevertheless, further study is necessary to explore these issues in greater detail. The findings of a study by Basyuni *et al*. (2021) indicate that selecting the right species and employing effective planting techniques can markedly increase seedling survival rates and hasten the restoration of ecosystems. Additionally, using techniques that create optimal conditions for mangrove growth, such as developing waterways to improve water circulation and reduce excessive salinity, has proven beneficial. Moreover, the study by Sasmito *et al.* (2019) employed the integrated coastal zone management (ICZM) method to encourage local community involvement in decision-making related to coastal resource management. Engaging in this process is crucial to guarantee that policies are tailored to meet local needs and circumstances. This method further underscores the need for sustainable management of natural resources, including fisheries and tourism, to ensure that economic gains do not adversely affect mangrove ecosystems. These strategies may bolster the resilience of Rhizophora species in areas facing alterations in land use. Land use changes significantly impact *Rhizophora* species, affecting their growth, distribution, and ecological functions. Urbanization, agriculture, and industrial development often lead to habitat loss and fragmentation, disrupting the natural dynamics of mangrove ecosystems. Such changes can result in a reorganization of species dominance, with more adaptable species potentially outcompeting others, which can contribute to a decrease in biodiversity. Furthermore, alterations in hydrology and sedimentation patterns due to land use changes can affect the growth conditions of *Rhizophora*. This ultimately impacts their ability to sequester carbon and provide essential ecosystem services such as coastal protection and habitat for marine life (Alongi, 2018; Booi *et al.,* 2022). Furthermore, changes in land use play a crucial role in influencing the resilience of Rhizophora species amid the challenges posed by climate change. These species are often sensitive to variations in salinity, temperature, and nutrient availability, making their physiological responses vulnerable to human activities (Alongi, 2018; Sanchez *et al.,* 2021). The reduction of freshwater inflow caused by land development can lead to heightened salinity levels, which may stress mangrove species, ultimately resulting in decreased growth and increased mortality rate. This highlights the importance of implementing effective management and restoration strategies that consider the specific ecological requirements of *Rhizophora* species. Such measures are crucial for enhancing their resilience and ensuring the sustainability of mangrove ecosystems (Ellison *et al.,* 2020; Ferreira *et al.,* 2023).

CONCLUSION

An examination of leaf morphology among three species of *Rhizophora* indicated that *R. apiculata* and *R. mucronata*, which frequently coexist in mangrove environments, display comparable leaf shapes and coloration. This study assessed the impacts of land use changes on the morphological characteristics of *R. apiculata*, *R. mucronata*, and *R. stylosa*. The analysis indicated that habitat conditions significantly influence certain morphological characteristics of *R. mucronata*, with lamina length (F=45.43) and leaf width (F=34.04) showing strong effects, while petiole length was moderately affected (F=13.64) and weakly influenced (F=5.693). *Rhizophora stylosa* was only found in Percut Sei Tuan and Sitardas, with its absence in Medan Belawan attributed to unfavorable substrate and habitat conditions. The statistical analysis indicated that there were only slight morphological variations among the various ecosystems, with the exceptions of lamina length (F=28.68) and leaf tip (F=24.71). In contrast, petiole length (F=2.81) and leaf width (F=0.6409) did not demonstrate any significant effects. Observations of stomatal anatomy revealed that variations in land use influence leaf structure, particularly in terms of density, stomatal index, and stomatal length. The

stomatal type in *Rhizophora* spp. predominantly exhibits anomocytic forms in *R. apiculata* and *R. stylosa*, characterized by circular anticlinal walls. In *R. apiculata*, stomatal density (F=1.489) was not significantly affected, whereas stomatal index (F=19.69), length (F=26.19), and width (F=37.84) showed significant effects, indicating high sensitivity to growth area differences. In terms of morphological and anatomical changes, *Rhizophora* mucronata was more sensitive than *R. apiculata*, while *R. stylosa* proved to be more resilient to land use changes occurring in Percut Sei Tuan and Sitardas. Salinity levels varied across study sites, with Percut Sei Tuan recording the highest average salinity at 33.06 ppm, compared to lower levels in Medan Belawan (12.67 ppm) and Sitardas (13.36 ppm). The results of the PCA indicated considerable variability in the data from Percut Sei Tuan, particularly along the first principal component, which suggests a distinct profile relative to other sites. Meanwhile, Medan Belawan and Sitardas were closely clustered, reflecting a greater similarity and reduced variation between them. This study concludes that *R. stylosa* shows limited tolerance to environmental changes, *R. mucronata* possesses significant morphological and anatomical flexibility, and *R. apiculata* is highly responsive to environmental variations without necessitating changes in leaf shape and structure.

AUTHOR CONTRIBUTIONS

A.B. Rangkuti, the corresponding author, has contributed in conceived and designed the experiments, analyzed and interpreted the data, wrote the manuscript draft, reviewed and finalized the final draft. P. Peniwidiyanti conceived and designed the experiments, supervised morphological and anatomical data collection, analyzed and interpreted the data, and wrote the manuscript draft. M. Basyuni reviewed and finalized the final draft. D. Elfiati reviewed and finalized the final draft. A. Susilowati analyzed and interpreted the data, wrote the manuscript draft, and reviewed and finalized the final draft. A. Mubaraq visualization, reviewed and finalized the final draft. M.R. Hariri conceived and designed the experiments, supervised morphological data collection, analyzed and interpreted the data, and wrote the manuscript draft. A.P. Dewi conceived and designed the experiments, supervised anatomical data collection, analyzed and interpreted the data, and wrote the manuscript draft. F. Indriani prepared the manuscript and organized the text. F.G. Dwiyanti reviewed the manuscript draft. B. Slamet conceived and designed the experiments. R.A. Syahputra reviewed the manuscript draft. All authors have approved the final manuscript submitted.

ACKNOWLEDGEMENT

This study is an output of the Equity project research program and the establishment and development of scientific clusters and science and technology centers of excellence in 2023, with number: [4921 / UN5.1.R /SK /PM / 2023]. Assignment of Mangrove Center of Excellence, University of North Sumatra.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
µm	Micrometer
±	Plus-minus
AHP	Analytical hierarchy process
ANOVA	Analysis of variance
cm	Centimeter
CO_2	Carbon dioxide
EC	Electro conductivity
F	F-test
FAO	Food and Agriculture Organization
GIS	Geographic information system
GY	Green yellow
Ha	Hornblende Andesite
ha	Hectare
ICZM	Integrated coastal zone management
LL	Lamina length
LP	Leaves point
LW	Leaves width
m/s	Meter per second
Mha	Million hectares
mm	Milimeter
mS/cm	Milisiemens per centimeter
PAST	Paleontological statistics
PC	Principal components
PCA	Principal component analysis
PES	payment for ecosystem services
pH	Potential of hydrogen
PL	Petiole length
ppm	Parts per million
R. apiculata	Rhizophora apiculata
R. mucronata	Rhizophora mucronata
R. stylosa	*Rhizophora stylosa*
SL	Stipule length
TSD	Total disolved solid
VPD	Vapor pressure deficit

REFERENCES

Abdillah, S.; Harahab, N.; Primyastanto, M; Semedi B., (2020). Analysis of suitability and carrying capacity of mangrove ecosystem for ecotourism in Lembar Village, West Lombok District, Indonesia. Biodiversitas. 22(2): 596-604 **(9 pages).**

Adame M.F.; Reef, R.; Santini, N.S.; Najera, E.; Turschwell, M.P.; Hayes, M.A.; Masque, P.; Lovelock C.E., (2021). Mangroves in arid regions: Ecology, threats, and opportunities. Estuar. Coast. Shelf Sci., 248: 106796 **(10 pages).**

Akram, H.; Hussain, S.; Mazumdar, P.; Chua, K.O.; Butt, T.E.; Harikrishna, J.A., (2023). Mangrove health: A review of functions, threats, and challenges associated with mangrove management practices. For., 14(9): 1698 **(38 pages)**.

Alongi, D.M., (2018). Impact of global change on nutrient dynamics in mangrove forests. Forests. 9(10): p.596 **(13 pages)**.

Asari, N.; Suratman, M.N.; Mohd Ayob N.A.; Abdul Hamid, N.H., (2021). Mangrove as a natural barrier to environmental risks and coastal protection. In: Rastogi RP, Phulwaria M, Gupta DK (eds). Mangroves: Ecol. Biodivers. Manage., Springer. 305–322 **(18 pages).**

Azis, S.S.A.; Sipan, I.; Sapri, M.; Zafirah, A.M., (2018). Creating an innocuous mangrove ecosystem: Understanding the influence of ecotourism products from Malaysian and international perspectives. Ocean Coast. Manage., 165: 416-427 **(12 pages)**.

Badave, S.: Charles, P.E.; Chougule, M.N.; Nadaf, M.F.; Pujari, M.A., (2023). Protection of coastal area by using seawall and mangrove trees. Intl. J. New Media Stud., 10(1): 152-157 **(6 pages)**.

Barati, A.A.; Zhoolideh, M.; Azadi, H.; Lee, J.H.; Scheffran, J., (2023). Interactions of land-use cover and climate change at global level: How to mitigate the environmental risks and warming effects. Ecol. Indic., 146: 109829 **(10 pages)**.

Baroga, J.B.; Buot, I.E.J., (2014). Leaf architecture of ten species of Philippine Terminalia Linn. (Combretaceae). Int. Res. J. Biol. Sci., 3(3): 83-88 **(6 pages)**.

Basyuni, M.; Sasmito, S.D.; Analuddin, K.; Ulqodry, T.Z.; Saragi-Sasmito, M.F.; Eddy, S.; Milantara, N., (2022). Mangrove biodiversity, conservation and roles for livelihoods in Indonesia. In: Mangroves: Biodiversity, livelihoods and conservation. Springer Nature Singapore, 397-445 **(49 pages).**

Basyuni, M.; Slamet, B.; Sulistiyono, N.; Munir, E.; Vovides, A.; Bunting, P., (2021). Physicochemical characteristics, nutrients, and fish production in different types of mangrove forests in North Sumatra and the Aceh Provinces of Indonesia. Kuwait J. Sci., 48(3): 1-14 **(14 pages)**.

Bindiya, E.S.; Sreekanth, P.M.; Bhat, S.G., (2023). Conservation and Management of Mangrove Ecosystem in Diverse Perspectives. In: Sukumaran STTRK (eds). Conservation and Sustainable Utilization of Bioresources. Sustainable Dev. Biodivers., Springer. 323–352 **(30 pages)**.

Booi, S.; Mishi, S.; Andersen, O., (2022). Ecosystem services: a systematic review of provisioning and cultural ecosystem services in estuaries. Sustainability, 14(12): 7252 **(29 pages)**.

Bryan, J.E.; Shearman, P.L.; Asner, G.P.; Knapp, D.E.; Aoro, G.; Lokes, B., (2013). Extreme differences in forest degradation in Borneo: Comparing practices in Sarawak Sabah and Brunei. Plos One, 8(7): 1-7 **(7 pages)**.

Bryan-Brown, D.N.; Connolly, R.M.; Richards, D.R., (2020). Global Trends in Mangrove Forest Fragmentation. Sci. Rep., 10: 7117 **(8 pages)**.

Cahyaningsih, A.P.; Deanova, A.K.; Pristiawati, C.M.; Ulumuddin, Y.I.; Kusumaningrum, L.; Setyawan, A.D., (2022). Causes and

impacts of anthropogenic activities on mangrove deforestation and degradation in Indonesia. Int. J. Bonorowo Wet., 12(1): 12-22 **(11 pages)**.

Carugati, L.; Gatto, B.; Rastelli, E., Lo Martire, M.; Coral, C.; Greco, S.; Danovaro, R., (2018) Impact of mangrove forests degradation on biodiversity and ecosystem functioning. Sci. Rep., 8: 13298 **(11 pages)**.

Chen, C.I.; Lin, K.H.; Huang, M.Y.; Wong, S.L.; Liao, T.S.; Chen, M.N.; Weng, J.H.; Hsueh, M.L.; Lai, Y.H.; Wang, C.W., (2022). Photosynthesis in response to different salinities and immersions of two native Rhizophoraceae mangroves. Cells. 11(19): 3054 **(15 pages)**.

Cloern, J.E.; Abreu, P.C.; Carstensen, J.; Chauvaud, L.; Elmgren, R.; Grall, J.; Greening, H.; Johansson, J.O.R.; Kahru, M.; Sherwood, E.T.; Xu, J., (2016). Human activities and climate variability drive fast-paced change across the world's estuarine–coastal ecosystems. Glob. Chang. Biol. 22(2): 513-529 **(17 pages)**.

Contreras, D.M.; Cantera Kintz, J.; Sánchez González, A.;Mancera E., (2018). Food web structure and trophic relations in a riverine mangrove system of the Tropical Eastern Pacific, Central Coast of Colombia. Estuar. Coast., 41: 1511-1521 **(11 pages)**.

Dilcher, D.L., (1974). Approaches to the identification of angiosperm leaf remains. Bot. Rev., 40(1): 1-160 **(160 pages)**.

Ellison, A.M.; Felson, A.J.; Friess, D.A., (2020). Mangrove rehabilitation and restoration as experimental adaptive management. Front. Marin. Sci. 7: 327 **(19 pages)**.

FAO, (2020). Global forest resources assessment 2020: Main report. Food and Agriculture Organization. Rome, 1-186 **(186 Pages).**

Feng, W.; Lindner, H.; Robbins, N.E.; Dinneny, J.R., (2016). Growing out of stress: the role of cell-and organ-scale growth control in plant water-stress responses. The Plant Cell, 28(8): 1769-1782 **(14 pages).**

Ferreira, A.C., de Lacerda, L.D., Rodrigues, J.V.M. and Bezerra, L.E.A., (2023). New contributions to mangrove rehabilitation/ restoration protocols and practices. Wetl. Ecol. Manage. 31(1): 89-114 **(26 pages)**.

Ferreira, C.A.; Lacerda, D.L., (2016). Degradation and conservation of brazilian mangroves, status and perspectives. Ocean Coast. Manage., 125: 38-46 **(9 pages)**.

Fox, R. J.; Donelson, J. M.; Schunter, C.; Ravasi, T.; Gaitán-Espitia, J.D., (2019). Beyond buying time: the role of plasticity in phenotypic adaptation to rapid environmental change. Philos. Trans. R. Soc. B, Biol. Sci. 374(1768): 20180174 **(9 pages)**.

Friess, D.A.; Thompson, B.S.; Brown, B.; Amir, A.A.; Cameron, C.; Koldewey, H.J.; Sasmito, S.D.; Sidik, F., (2016). Policy challenges and approaches fot the conservation of mangrove forests in Southeast Asia. Conserv Biol 30(5): 933-949 **(18 pages)**.

Friess, D.A.; Yando, E.S.; Alemu J.B.; Wong L.W.; Soto, S.D.; Bhatia, N., (2020). Ecosystem services and disservices of mangrove forests and salt marshes. Oceanogr. Mar. Biol., 58: 107-142 **(36 pages)**.

Gerona-Daga, M.E.B.; Salmo SG III., (2022). A systematic review of mangrove restoration studies in Southeast Asia: Challenges and opportunities for the United Nation's Decade on Ecosystem Restoration. Front. Mar. Sci. 9:987737 **(23 pages)**.

Greaver, T.L.; Clark, C.M.; Compton, J.E.; Vallano, D.; Talhelm, A.F.; Weaver, C.P.; Band, L.E.; Baron, J.S.; Davidson, E.A.; Tague, C.L.; Felker-Quinn, E., (2016). Key ecological responses to nitrogen are altered by climate change. Nat. Clim. Chang. 6(9): 836-843 **(8 pages)**.

Hammer, O., & Harper, D. A. (2024). Paleontological data analysis: 2nd Edition. John Wiley & Sons, 1-400 **(400 pages).**

Hanggara, B.B.; Murdiyarso, D.; Ginting, Y.R.S.; Widha, Y.L.; Panjaitan, G.Y.; Lubis, A.A., 2021. Effects of diverse mangrove management practices on forest structure, carbon dynamics and sedimentation in North Sumatra, Indonesia. Estuar. Coast. Shelf Sci 259(2021): 107467 **(13 pages)**.

Harefa, M.S.; Wardani, A.; Ulfami, T.; Tarigan, R.P.; Rahmadi, M.T., (2022). The impact of community activities on aquatic ecosystems in Belawan Sicanang Village. J. Laguna Geo., 1(2): 29-34 (**6 pages**).

Hasibuan, I.M.; Amelia, R.; Bimantara, Y.; Susetya, I.E.; Susilowati, A.; Basyuni, M., (2021). Vegetation and macrozoobenthos diversity in the Percut Sei Tuan mangrove forest, North Sumatra, Indonesia. Biodiversitas. 22(12): 5600 – 5608 (**10 pages**).

Hilmi, E.; Sari, L.K.; Siregar, A.S.; Sulistyo, I.; Mahdiana, A.; Junaedi, T.; Prayogo, N.A., (2021). Tannins in mangrove plants in segara anakan lagoon, central java, indonesia. Biodiversitas J. Biol. Divers., 22(8): 3508-3516 **(9 pages).**

Ibrahim, H.M.; Alshaibani, A.R.; Al-Gifri, A.N.A., (2021). Epidermal properties of Aloe vacillans Forsskal leaf and its taxonomical significance in classifying its two forms. PSM Biol. Res., 6(3), 76-83 **(8 pages).**

Ilman, M.; Dargusch, P.; Dart, P.; Onrizal, (2016). A historicalanalysis of the drivers of loss and degradation Indonesia's mangroves. Land Use Policy. 54: 448-459 **(12 pages).**

Inoue, T.; Fujimura, T.; Noguchi, K., (2024). Growth, morphology and respiratory cost responses to salinity in the mangrove plant *Rhizophora stylosa* depend on growth temperature. Plant Cell Environ. 48(2): 965 – 977 **(13 pages)**.

Iqbal, U.; Azam, A.; Ahmad, K.S.; Mumtaz, S.; Mehmood, A.; Naz, N.; Usman, Z.; Abbas, H.; Akram, M., (2024). Unveiling the ecological dominance of button mangrove (*Conocarpus erectus* L.) through microstructural and functional traits modifications across heterogenic environmental conditions. Bot. Stud. 65(1): 36 **(22 pages)**.

Kalasuba, K.; Miranti, M.; Rahayuningsih, S.R.; Safriansyah, W.; Syamsuri, R.R.P.; Farabi, K.; Oktavia, D.; Alhasnawi, A.N.; Doni, F., (2023). Red Mangrove (*Rhizophora stylosa* Griff.)—A review of its botany, phytochemistry, pharmacological activities, and prospects. Plants. 12, 2196 (**16 pages**).

Kiani-Pouya, A.; Rasouli, F.; Rabbi, B.; Falakboland, Z.; Yong, M.; Chen, Z.H.; Shabala, S.. (2020). Stomatal traits as a determinant of superior salinity tolerance in wild barley. J. Plant Physiol., 245: 153108 **(9 pages).**

Koh, H.L.; Teh, S.Y.; Kh'Ng, X.Y.; Raja Barizan, R.S., (2018). Mangrove forests: Protection against and resilience to coastal disturbances. J. Trop. For. Sci., 30: 446-460 **(15 pages)**.

Lee, S.Y.; Primavera, J.H.; Dahdouh-Guebas, F.; McKee, K.; Bosire J.O.; Cannicci, S.; Diele, K.; Fromard, F.; Koedam, N.; Marchand, C.; Mendelssohn, I.: Mukherjee, N.; Record, S., (2014). Ecological role and services of tropical mangrove ecosystems: A reassessment. Global Ecol. Biogeogr., 23(7): 726-743 **(18 pages)**.

Leidonald, R.; Muhtadi, A.; Fadhila, A.; Susetya, I.E.; Panjaitan, E.T.; Sihombing, M.A.; Qaulya, U.; Rohim, N.; Firdaus, M.; Tampubolon, P.A., (2024). Spatial distribution and characteristics of microplastic particles in sediments at Belawan Estuary, North

Sumatra Province. 8th International Conference on Agriculture, Environment, and Food Security, IOP Conf. Series: Earth Environ. Sci. Trans. 1413 (2024) 012009 (**9 pages**).

Lovelock, C.E.; Barbier, E.; Duarte, C.M., (2022). Tackling the mangrove restoration challenge. PLoS Biol., 20(10): p.e3001836 **(15 pages)**.

Mitra, A., (2020). Ecosystem services of mangroves: An overview. In: Mangrove Forests in India. Springer. 1-32 **(32 pages)**.

Mubaraq, A.; Sembiring, M.; Widiastuti, E.; Fachrial, E.; Utomo, B.; Turjaman, M.; Sidik, F.; Ulumuddin, Y.I.; Arifanti, V.B.; Siregar, E.S.; Kajita, T.; Procheş, Ş.; Basyuni, M., (2024). Diversity and distribution of nitrifying bacteria play an important role in the nitrogen cycle in mangrove sediments. Global J. Environ. Sci. Manage., 10(4): 2145-2162 **(18 pages).**

Muhtadi, A.; Siregar, R.H.; Leidonald, R.; Harahap, Z.A., (2020). Status and mangrove distribution in Taman Pulau Kecil conservation area, Central Tapanuli District, North Sumatra Province. Depik J. Aquat. Coast. Fish. Sci., 9(2): 200-209 **(10 pages).**

Muro-Torres, V.M.; Amezcua. F.; Soto-Jiménez, M.; Balart, E.F.; Serviere Zaragoza, E.; Green, L.; Rajnohova, J., (2020). Primary sources and food web structure of a tropical wetland with high density of mangrove forest. Water. 12(11): 3105 **(18 pages).**

Murray, N.J.; Keith, D.A.; Bland, L.M.; Ferrari, R.; Lyons, M.B.; Lucas, R.; Nicholson, E., (2018). The role of satellite remote sensing in structured ecosystem risk assessments. Sci. Total Environ., 619: 249-257 **(9 pages).**

Ng, W.L.; Chan, H.T., (2012), Further observations on a natural *Rhizophora* hybrid population in Malaysia. ISME/GLOMIS Electron. J., 10(1): 1-3 **(3 pages).**

Noer, N.K.; Ørsted, M.; Schiffer, M.; Hoffmann, A.A.; Bahrndorff, S.; Kristensen, T.N., (2022), Into the wild—A field study on the evolutionary and ecological importance of thermal plasticity in ectotherms across temperate and tropical regions. Phil.Trans. R. Soc. B 377: 20210004 **(11 pages)**.

Paul, V.; Sharma, L.; Pandey, R.; Meena, R.C., (2017). Measurements of stomatal density and stomatal index on leaf/plant surfaces: in Physiological Techniques to Analyze the Impact of Climate Change on Crop Plants. Div. Plant Physiol., 27-30 **(4 pages).**

Perez, K.L.D.; Quimado, M.O.; Maldia, L.S.; Tinio, C.E.; Hernandez, J.O.; Combalicer, M.S., (2021). Effects of copper on the leaf morpho-anatomy of *Rhizophora mucronata*: Implications for mangrove ecosystem restoration. Biodiversitas. 22(4): 2058-2065 (**8 pages**).

Perez-Ceballos, R.; Zaldívar-Jiménez, A.; Canales-Delgadillo, J.; LópezAdame, H.; López-Portillo, J.; Merino-Ibarra, M., (2020). Determining hydrological flow paths to enhance restoration in impaired mangrove wetlands. PLoS One. 15: e0227665 (**20 Pages**).

Primavera, J.H.; Friess, D.A.: Van Lavieren, H.; Lee, S.Y., (2019). The mangrove ecosystem. In: Sheppard C (eds). World Seas: An Environmental Evaluation. Volume III: Ecological Issues and Environmental Impacts. Academic Press, Cambridge, Massachusetts. 1-34 **(34 pages)**.

Purnomo, D.W.; Prasetyo, L.B.; Widyatmoko, D.; Rushayati, S.B.; Usmadi, D.; Wati, R.K.; Solihah, S.M.A., (2023). Carbondioxide absorption capability and stomatal features of tropical lowland native trees. Bull. Kebun Raya. 26(2): 84-96 **(13 pages)**.

Qie, Y.D.; Zhang, Q.W.; McAdam, S.A.; Cao, K.F., (2024). Stomatal dynamics are regulated by leaf hydraulic traits and guard cell anatomy in nine true mangrove species. Plant Divers., 46(3): 395-405 **(11 pages).**

Quadros, A.F.; Helfer, V.; Nordhaus, I.; Reuter, H.; Zimmer, M., (2021). Functional traits of terrestrial plants in the intertidal: A review on mangrove trees. The Biol. Bull. 241(2): 123-139 **(17 pages)**.

Rahman, Lokollo, F.F.; Manuputty, G.D.; Hukubun, R.D.; Krisye.; Maryono; Wawo, M.; Wardiatno, Y., (2024). A review on the biodiversity and conservation of mangrove ecosystems in Indonesia. Biodiversity and Conservation 33: 875-903 **(29 pages)**.

Rahman, Wardiatno, Y.; Yulianda, F.; Rusmana, I., (2020). Socio-ecological system of carbon-based mangrove ecosystem on the coast of West MunaRegency,Southeast Sulawesi, Indonesia. AACL Bioflux. 13(2): 518-528 **(11 pages)**.

Rahmawaty, Rauf, A.; Harahap, M.M.; Kurniwan H., (2022). Land cover change impact analysis: an integration of remote sensing, GIS and DPSIR framework to deal with degraded land in Lepan Watershed,North Sumatera, Indonesia. Biodiversitas. 23(6): 3000–3011 **(12 pages)**.

Rahmawaty.; Siahaan, J.; Nuryawan, A.; Harahap, M.M.; Ismail, H.; Rauf, A.; Kurniawan, H.; Gandaseca, S.; Karuniasa, M., (2023). Mangrove cover change (2005–2019) in the Northern of Medan City, North Sumatra, Indonesia. Geocarto Int., 38:1, 2228742 **(28 pages)**.

Rangkuti, A.B.; Basyuni, M.; Elfiati, D.; Susetya, I.E.; Hutagaol, F.; Rangkuti, R.R., (2024). Analysis of mangrove vegetation on Mursala Island. IOP Conference Series: Earth Environ. Sci., 1352: 012080 (**9 pages**).

Rodriguez, K.A.R.; Pineda, J.E.M.; Melgarejo, L.M.; Calderón, J.H.M., (2018). Functional traits of eaves and forest structure of neotropical mangroves under di erent salinity and nitrogen regimes. Flora 239: 52 – 61 (**10 pages**).

Samiyarsih, S.; Suparjana, T.B.; Juwarno, (2016). Karakter anatomi daun tumbuhan mangrove akibat pencemaran di hutan mangrove Kabupaten Cilacap. Biosfera. 33(1): 31-36 **(6 pages).**

Sanchez, A.R.; Pineda, J.E.M.; Casas, X.M.; Calderón, J.H.M., (2021). Influence of edaphic salinity on leaf morphoanatomical functional traits on juvenile and adult trees of red mangrove (*Rhizophora mangle*): implications with relation to climate change. Forests. 12(11): p.1586 **(22 pages)**.

Sarveleni, A.E.; Tarmizi, H.B.; Thoha, A.S., (2023). Analysis of adaptation and mitigation recommendations for Banjir rob disasters in the coastal area of Belawan, Medan. Int. J. Multidiscip. Res. Growth Eval., 4(3): 839 – 845 **(7 pages)**.

Sasmito, S.D.; Taillardat, P.; Clendenning, J.N.; Cameron, C.; Friess, D.A.; Murdiyarso, D.; Hutley, L.B., (2019). Effect of land-use and land cover change on mangrove blue carbon: Asystematic review. Global Change Biol., 25(12): 4291-4302 **(12 pages).**

Setyawan, A.D.; Ragavan, P.; Basyuni, M.; Sarno, S., (2019). *Rhizophora mucronata* as source of foods and medicines. Int. J. Bonorowo Wetlands, 9(1): 42-55 **(14 pages).**

Setyawan, A.D.; Ulumuddin, Y.I.; Ragavan, P., (2014). Review: Mangrove hybrid of *Rhizophora* and its parental species in Indo-Malayan region. Nusantara Biosci., 6(1): 69-81 **(13 pages).**

Shamin-Shazwan, K.; Shahari, R.; Amri, C.N.A.C.; Kassim, Z.; Ahmad, Z., (2021). Morphological structures of *Rhizophora apiculata* Blume and *Rhizophora mucronata* Lam. Sci. Heritage

J., 5(1): 1-4 **(4 pages).**

Srikanth, S.; Lum, S.K.Y.; Chen, Z., (2016). Mangrove root: adaptations and ecological importance. Trees. 30: 451-465 **(15 pages)**.

Sulisiyono, N.; Amri, K.; Patana, P.; Thoha, A.S., (2019). Monitoring the spatial distribution of mangrove ecosystem in Percut Sei Tuan. Int. Conf. Nat. Resour. Technol., 2019: 38 – 41 (**4 pages**).

Tamimi, B.M.; W.A, W.J.; Nizam, M.S.; Zain, C.R.C.M., (2021). Temperature stress on physiological and morphological traits in *Rhizophora apiculata*. Baghdad Sci. J., 18(4): 1492-1500 **(9 pages).**

Wahyuni, E.; Zulhafandi, Hendris, Jarin, (2021). Detection of community knowledge level of economic, ecological benefits and causes of damage to mangrove forest ecosystems. IOP Conference Series: Earth Environ. Sci., 748: 012017 **(9 pages)**.

Wang, Y.S.; Gu, J.D., (2021). Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities. Int. Biodeterior. Biodegrad., 162: 105248 **(12 pages).**

Widiani, I.; Barus, T.A.; Wahyuningsih, H., (2021). Population of white shrimp (*Penaeus merguiensis*) in a mangrove ecosystem, Belawan, North Sumatra, Indonesia. Biodiversitas. 22(12): 5367 – 5374 (**8 pages**).

AUTHOR (S) BIOSKETCHES

Rangkuti, A.B., M.Si, Assistant Professor, Center of excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *baiqunirangkuti@usu.ac.id*
- ORCID: 0000-0002-3019-6038A
- Web of Science ResearcherID: GPK-3826-2022
- Scopus Author ID: 57211799613
- Homepage: https://fhut.usu.ac.id/en/lecturer/ahmad-baiquni-rangkuti

Peniwidiyanti, P., M.Si, Researcher, Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong, West Java, 16911, Indonesia.
- Email: *niwidiyan@gmail.com; peni003@brin.go.id*
- ORCID: 0000-0003-4019-165X
- Web of Science ResearcherID: NA
- Scopus Author ID: 57211193656
- Homepage: https://www.brin.go.id/

Basyuni, M., Ph.D., Professor, Center of excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *m.basyuni@usu.ac.id*
- ORCID: 0000-0003-1120-8571
- Web of Science ResearcherID: D-8537-2015
- Scopus Author ID: 15055287200
- Homepage: https://fhut.usu.ac.id/en/lecturer/mohammad-basyuni

Elfiati, D., Dr., Assistant Professor, Center of excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *deni1@usu.ac.id*
- ORCID: 0000-0003-4734-126X
- Web of Science ResearcherID: NA
- Scopus Author ID: 57194143537
- Homepage: https://fhut.usu.ac.id/id/dosen/deni-elfiati

Susilowati, A., Dr., Professor, Center of excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *arida.susilowati@usu.ac.id*
- ORCID: 0000-0001-9608-4787
- Web of Science ResearcherID: AAF-6384-2021
- Scopus Author ID: 56102433700
- Homepage: https://fhut.usu.ac.id/en/lecturer/arida-susilowati

Mubaraq, A., M.Agr., Ph.D Student, Center of Excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *alfian@students.usu.ac.id*
- ORCID: 0009-0005-9810-3896
- Web of Science ResearcherID: JTU-5714-2023
- Scopus Author ID: 59122664800
- Homepage: https://www.usu.ac.id/

Hariri, M.R, M.Si., Senior Researcher, Research Center for Biosystematics and Evolution, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong, West Java, 16911, Indonesia.
- Email: *muhammadrifqihariri@gmail.com; muha157@brin.go.id*
- ORCID: 0000-0003-0943-3198
- Web of Science ResearcherID: NA
- Scopus Author ID: 57195974945
- Homepage: https://www.brin.go.id/

AUTHOR (S) BIOSKETCHES

Dewi, A.P, M.Si., Researcher, Research Center for Biosystematics and Evolution, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong, West Java, 16911, Indonesia.
- Email: *asih004@brin.go.id*
- ORCID: 0000-0001-8051-8392
- Web of Science ResearcherID: NA
- Scopus Author ID: 57217189362
- Homepage: https://www.brin.go.id/

Indriani, F., Dr., Researcher, Research Center for Applied Botany, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Cibinong, West Java, 16911, Indonesia.
- Email: *fitri.indriani@brin.go.id*
- ORCID: 0000-0003-4344-2573
- Web of Science ResearcherID: NA
- Scopus Author ID: 57205764682
- Homepage: https://www.brin.go.id/

Dwiyanti,F.G, Ph.D., Assistant Professor, Department of Silviculture, Faculty of Forestry and Environment, IPB University , Ulin Street, IPB Dramaga Campus, Bogor, West Java, 16680, Indonesia.
- Email: *fifi_dwiyanti@apps.ipb.ac.id*
- ORCID: 0000-0003-0366-3259
- Web of Science ResearcherID: CAI-0480-2022
- Scopus Author ID: 56315586900
- Homepage: https://www.ipb.ac.id

Slamet, B., Dr., Assistant Professor, Center of excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *bejo@usu.ac.id*
- ORCID: 0000-0003-0346-9595
- Web of Science ResearcherID: AAC-8673-2020
- Scopus Author ID: 57189664036
- Homepage: https://fhut.usu.ac.id/id/dosen/bejo-slamet

Hartini, K.S., Dr., Assistant Professor, Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Medan 20155, Indonesia.
- Email: *kansih_sri_hartini@usu.ac.id*
- ORCID: 0000-0003-1005-9121
- Web of Science ResearcherID: AAM-6995-2020
- Scopus Author ID: 57193788626
- Homepage: https://www.usu.ac.id/

Syahputra, R.A., M.Sc., Associate Professor, Department of Chemistry, Universitas Negeri Medan, Jalan Willem Iskandar, Pasar V, Medan Estate, Medan 20221, North Sumatera, Indonesia.
- Email: *rickyandi@unimed.ac.id*
- ORCID: 0000-0003-1045-2978
- Web of Science ResearcherID: NA
- Scopus Author ID: 57219301149
- Homepage: https://unimed.ac.id/

HOW TO CITE THIS ARTICLE

Rangkuti, A.B.; Peniwidiyanti, P.; Basyuni, M.; Elfiati, D.; Susilowati, A.; Mubaraq, A.; Hariri, M.R.; Dewi, A.P.; Indriani, F.; Dwiyanti, F.G.; Slamet, B.; Hartini, K.S.; Syahputra, R.A., (2025). The impact of land use change on morphological and anatomical adaptations of Rhizophora species. Global J. Environ. Sci. Manage., 11(2): 771-790.

DOI: 10.22034/gjesm.2025.02.22

URL: https://www.gjesm.net/article_719952.html

Global J. Environ. Sci. Manage. 11(2): 791-804, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Green chemistry approach to formaldehyde detection using fish albumin-modified gold electrodes

T.P.H. Hutapea[1], Suprapto[2], M.Y. Syaputra[2,3], F. Kurniawan[2,*]

[1] *Fisheries Product Technology Department, Faculty of Fishery and Marine Science, University of Borneo Tarakan, North Borneo 77115 Indonesia*

[2] *Chemistry Department, Institute Teknologi Sepuluh Nopember, Surabaya, East Java 60111 Indonesia*

[3] *Graduate School of Science and Engineering, Saga University, Honjomachi, Saga 840-8502, Japan*

ARTICLE INFO

Article History:
Received 16 November 2024
Revised 21 January 2025
Accepted 26 Feburary 2025

Keywords:
Electrode
Fish albumin
Formaldehyde detection
Nash method

ABSTRACT

BACKGROUND AND OBJECTIVES: Formaldehyde in food or the environment poses significant health risks, as it is a known carcinogen that can cause respiratory issues skin irritation, and long-term exposure can lead to serious diseases such as cancer. The presence of formaldehyde is detectable in various environments, including food and water. A newly developed gold electrode, enhanced with fish albumin, has been created for the purpose of detecting formaldehyde, adhering to the principles of green chemistry. Fish albumin, which contains amino acids such as glycine, lysine, and histidine, can react with formaldehyde. This level of reactivity implies that fish albumin can serve as an effective and sustainable material for formaldehyde sensor applications. The objectives of this study were to make albumin-modified electrodes used for formaldehyde detection applied for the fish in case fishermen generally use formaldehyde to preserve the fish they bring ashore. This formaldehyde helps maintain the freshness of the fish during the handling and transportation process.
METHODS: The fish albumin was used from the self-extraction of snakehead fish (Channa striata) using water as a solvent. Fish albumin was combined with paraffin in a specific ratio, subsequently heated on a hot plate and stirred until a homogeneous mixture was achieved. The liquid was poured into a small glass tube, with one of the ends connected to gold. The electrode was ready to be used after the liquid became solid. All experiments conducted for the detection of formaldehyde utilized the cyclic voltammetry method. The potential measurement was between 0 volt and +1.8 volt with a 100 millivolt per second scan rate.
FINDINGS: The electrode works well in acidic conditions by showing a significant formaldehyde signal compared to alkaline and neutral conditions. The linear analysis range was 0.1 ~ 3 millimolars with a detection limit of 4.07 micromolars, and the sensitivity was 20.365 microampere millimolars per square millimeter. This electrode was utilized to assess the level of formaldehyde while accounting for the interference from methanol, ethanol, glycerol, and glucose. This method was also applied to the real samples and simultaneously compared to the standard method (Nash method) for formaldehyde detection.
CONCLUSION: The electrode exhibits excellent performance with high sensitivity and selectivity for formaldehyde detection under acidic conditions. With its low detection limit, the electrode allows for highly accurate detection of formaldehyde measurement. Methanol, ethanol, glucose, and glycerol do not interfere with detection. Additionally, the electrode demonstrates good repeatability and delivers accuracy comparable to the standard Nash method, making it a promising alternative for formaldehyde detection. A key benefit of the proposed method is that it eliminates the need to add reagents to the samples.

DOI: 10.22034/gjesm.2025.02.23

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
33

NUMBER OF FIGURES
8

NUMBER OF TABLES
5

*Corresponding Author:
Email: *fredy@its.ac.id*
Phone: +821 4126 4818
ORCID: 0000-0002-9777-0989

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Albumin is a globular protein characterized by its solubility in water and its tendency to coagulate when heated. It contains over 500 amino acids and is present in humans, plants, and animals alike. It is usually called human serum albumin (HSA) in humans and 2S albumin in plants. Albumin is widely present among different animal species; for instance, bovine serum albumin (BSA) is sourced from cattle, while ovalbumin (OVA) is derived from eggs (Hutapea *et al*., 2023; Hou *et al*., 2023). Other sources of albumin are found in various groups of animals, such as mammals, reptiles, amphibians, birds and fishes. One fish species with a high albumin content, fish albumin (FA), widely found in Indonesia and used in this study is *Channa striata*. Albumin can be applied in various fields, such as drug delivery (Tiwari *et al*., 2021), wound healing (Liu *et al*., 2023), corrosion inhibitors (Kaseem and Ko, 2021) and sensors (Li *et al*., 2024). In sensor applications, albumin serves as an effective sensor material, as its proteins possess active sites that can engage with compatible molecule. Various previous studies have reported the use of protein-based materials in sensor technology, such as egg white (Padmalaya *et al*., 2024), gelatin (Hutapea *et al*., 2024) and including albumin. In these applications, the commonly used forms of albumin are HSA and Bovine BSA. In contrast, there is no documented use of FA in sensor technologies. FA has been reported in various industrial sectors, such as the fish feed industry to improve nutritional quality, the food industry as an additive, as well as in the health and pharmaceutical sectors as a component in drug formulations for wound healing (Soedjanaatmadja *et al*., 2021). The extensive applicability of fish albumin underscores its diverse and high value properties. However, although there have been many studies exploring its use in various fields, to date there have been no reports that specifically discuss its use as a sensor material. The composition of FA includes multiple amino acids, such as glycine, lysine, and histidine (Nurfaidah *et al*., 2024). On the other work, these amino acids can react with formaldehyde (Jia *et al*., 2024). It is conceivable that FA could engage with formaldehyde. Consequently, this study will incorporate FA in sensor applications aimed at formaldehyde detection. Formaldehyde is a compound absorbed quickly in human and animal respiratory and gastrointestinal tracts. It can be converted into formic acid and, after that, into carbon dioxide in the human body's metabolism. In humans and animals, formaldehyde has a very short biological half-life, estimated to be approximately 60 seconds. It explains that formaldehyde is very harmful to human health. Formaldehyde is also a carcinogenic compound that can cause cancer (Soltanpour *et al*., 2022). Nevertheless, formaldehyde is widely used in various industries as a raw material for adhesives (Torun, 2022; Dorieh *et al*., 2022), disinfectants (Fadeyibi *et al*., 2024), and cosmetics (Sánchez *et al*., 2021). Additionally, the use of formaldehyde as a food preservative is conducted illegally (Nayak *et al*., 2024). The use of formaldehyde compounds in industry and foodstuffs can cause formaldehyde pollution. Controlling formaldehyde pollution is imperative. Timely detection of formaldehyde plays a vital role in the effective management of this pollutant. Various methods have been carried out in determining formaldehyde, including chromatographic methods, spectrophotometry (Lian *et al*., 2021) and electrochemical sensor (Li *et al*., 2022; Wicaksono *et al*., 2022). The chromatographic method generally takes a relatively long time to accomplish. Furthermore, the process of preparing and selecting the suitable solvent is time-consuming. Like the chromatographic method, the spectrophotometric method also requires a relatively long time and process in sample preparation. The measured sample must be reacted with other compounds to form complex compounds that can absorb light with wavelengths >185 nanometers (nm). In contrast, the electrochemical sensor technique is not only easier and faster but also provides greater accuracy at a lower expense, positioning it as the optimal choice for formaldehyde control. Consequently, the study aimed to design a new sensor for formaldehyde detection by implementing an electrochemical method. The sensor was a gold electrode (GE) modified with FA extracted independently from snakehead fish (*Channa striata*). The fabrication of the sensor is very simple, namely by immobilizing FA on the surface of a gold electrode. The sensor has good selectivity and sensitivity to formaldehyde with a low limit of detection (LOD). Moreover, the results of formaldehyde assessments on real samples conducted with the sensor and the conventional method did not exhibit significant differences at the 95 percent (%) confidence level. The aims of this study

is to make albumin-modified electrodes used for formaldehyde detection applied for the fish in case fishermen generally use formaldehyde to preserve the fish they bring ashore. This formaldehyde helps maintain the freshness of the fish during the handling and transportation process. The study aims to make an environmentally friendly sensor from FA to detect formaldehyde. The use of environmentally conscious sensors represents a viable strategy for achieving sustainability in the environment. Apart from that, other methods such as adsorption of dangerous compounds (Samimi, 2023), use of environmentally friendly polymers (Rizki *et al*., 2024), effective waste management (Suprihatin *et al*., 2024), and early detection of toxic compounds (Hermanto *et al.,* 2023) also play an important role in maintaining a healthy, safe and protected environment from toxic compounds (Kiswandono *et al.,* 2024). This study has been carried out in Surabaya, Indonesia, in 2024.

MATERIALS AND METHODS

Materials

The materials used in this study were paraffin, potassium hydroxide, potassium chloride, glucose, chloric acid 37%, methanol 99.98%, ethanol 99,98%, glycerol 98%, and formaldehyde 37% purchased from Sigma-Aldrich. The FA was utilized for the self-extraction of snakehead fish (*Channa striata*), following previously documented procedures that involved water as a solvent (Hutapea *et al*., 2022). In short, the snakehead fish meat is blended until smooth, and water is added. Then, the extraction process was done by heating the mixture at 50 degrees Celsius (^{0}C) for 20 minutes. Then, the mixture was filtered, and n-hexane was added with a ratio of 1:0.25 in a separation funnel. Once whisked and allowed to sit for one minute, the liquid separates into two distinct phases. In the final stage, the aqueous phase was separated and dried in an oven at 50 ^{0}C until a solid extract was obtained. The fish sample used was Tongkol fish (*Euthynnus affinis*) obtained from a traditional market in Surabaya, Indonesia.

Apparatus

The main instrumentation for all measurements in this study was an AUTO LAB PGSTAT 128 N with the three-electrode system (Metrohm, Germany). The working electrode was a fish albumin modified gold electrodes (FA-GE), with silver/silver chloride (Ag/AgCl) in potassium chloride three molars (KCl 3M) as the reference electrode and platinum wire as the auxiliary electrode. In addition to the primary equipment, the experiment incorporated an analytical balance, hot plates, an ultrasonic cleaner, and a stereo microscope, specifically the Olympus SZ61, which was equipped with a digital camera.

Fabrication of FA-GE

Gold wire with a diameter of 1 millimeter (mm) was cut into 5 centimeters (cm) long and then inserted into tubular glass. On the other hand, FA and paraffin were mixed in a watch glass at a definite ratio. The ratios of FA and paraffin used in this experiment were 10:0, 9:1, 8:2, 7:3, and 6:4, respectively, to get optimum composition. The mixture was subjected to heating on a hot plate until the paraffin melted and achieved a homogeneous consistency. Subsequently, this uniform mixture was transferred into the end of the tubular glass that had been prepared with gold wire in advance. The mixture on the end of the tubular is flattened and allowed to cool and solidify to form a working electrode ready for further experiment. Fig. 1 shows the fabrication process of the FA-GE.

Electrochemical characterization of FA-GE

All performances of FA-GE for formaldehyde detection used the cyclic voltammetry (CV) technique; otherwise, it will be mentioned. The potential measurement was between 0 volt (V) and +1.8 V with a 100 millivolt per second (mV/s) scan rate. The effect of electrode modification using FA was studied by measuring 1 millimolar (mM) formaldehyde in 0.1 normality of hydrochloride acid (NHCl). Using GE, paraffin-modified gold electrodes (P-GE), and FA-GE, respectively. The effect of potential of hydrogen (pH) on the measurement was investigated by analyzing the same solution at pH values of 1,7 and 13. The effect of the scan rate was studied by measuring the same solution at various scan rates (50, 100, 150, 200, 250, 300, and 350/mVs). The concentration dependence was also studied by measuring various concentrations of formaldehyde solutions (0.1, 0.25, 0.50, 1, 1.5, 2.0, 2.5, and 3 mM). The selectivity of FA-GE was studied by individuals measuring methanol, ethanol, glucose, and glycerol solutions of 3 mM in 0.1 N HCl. Measurements were also taken for the mixtures of formaldehyde with methanol, ethanol, glucose, and glycerol. The repeatability of the electrode was performed by measuring 1 mM

of formaldehyde 3 times using a single electrode. Supplementary experiments were undertaken to investigate the performance of electrode fabrication by testing the same solution using 5 different FA-GEs. The performance of FA-GE was compared with the standard method (nash method) in real sample (fish) measurements with 3 samples repeated 3 times.

RESULTS AND DISCUSSION

Fabrication of FA-GE

The function of the paraffin in fabricating the electrode is as a binder. Given that paraffin exhibits non-conductive characteristics, it is preferable to use it sparingly in sensor-related applications. A potential drawback of minimizing binder content is the decreased fragility of the electrode. Table 1 illustrates the optimization of the paraffin ratio employed. It shows that the best ratio FA: Paraffin with the minimum paraffin is 6:4. At this ratio, the mixture of fish albumin and paraffin blends perfectly, forming a material that can solidify optimally in the electrode tube. This combination demonstrates excellent mechanical stability, guaranteeing that the material remains intact and does not dissolve or lose color when immersed in a solution. Consequently, this combination can be dependably utilized in electrode applications without undergoing considerable structural deterioration. An alternative ratio fails to create a solid structure, rendering it unsuitable for electrode use. This specific ratio is employed to fabricate electrodes for subsequent experiments.

The electrode surface was prepared by smoothing it with abrasive paper, rinsing it with deionized water, and then drying it at room temperature before use. The layer thickness has an important role in determining the sensitivity and detection limit, because it directly influences the electron transfer rate. Therefore, in the FA-GE fabrication process, efforts are made to

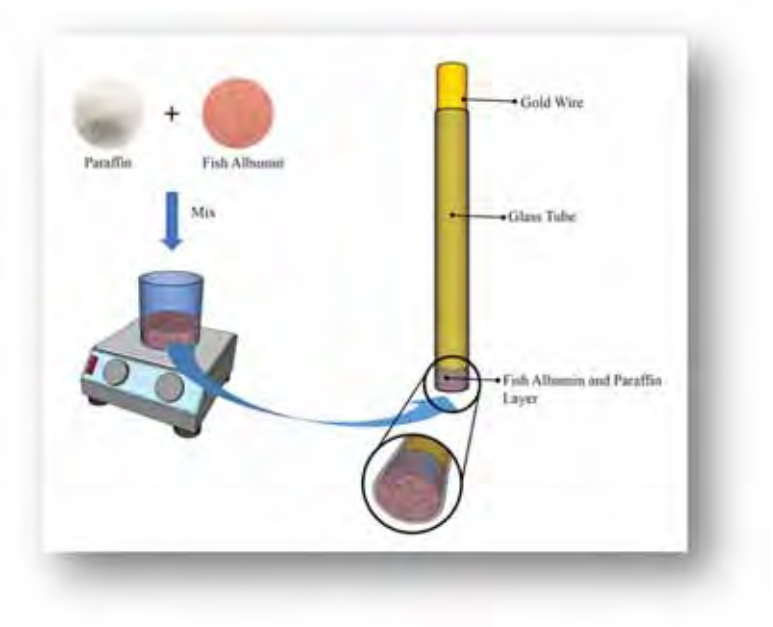


Fig. 1: The fabrication process of FA-GE

Table 1: Mass ratio FA and paraffin in FA-GE fabrication

FA	Paraffin	Solid form	Explanation
10	0	No	Non-homogeneous mixture
9	1	No	Non-homogeneous mixture
8	2	No	Non-homogeneous mixture
7	3	No	Non-homogeneous mixture
6	4	Yes	Homogeneous mixture

produce a very thin layer, around 0.2 mm, in order to optimize sensor performance. In Fig. 2, the electrode surface is depicted in two states: before coating (A) and after coating (B). The noticeable change in color between these two images confirms the successful application of the coating on the GE. This particular electrode is designated as FA-GE.

Electrochemical characterization of FA-GE

The effect of FA as an electrode modification

Fig. 3 shows the effect of FA modification on the GE using CV. GE voltammogram (green) has no response to formaldehyde. In comparison to formaldehyde, the blank (dashed) demonstrated a higher peak oxidation current. A similar condition was also shown

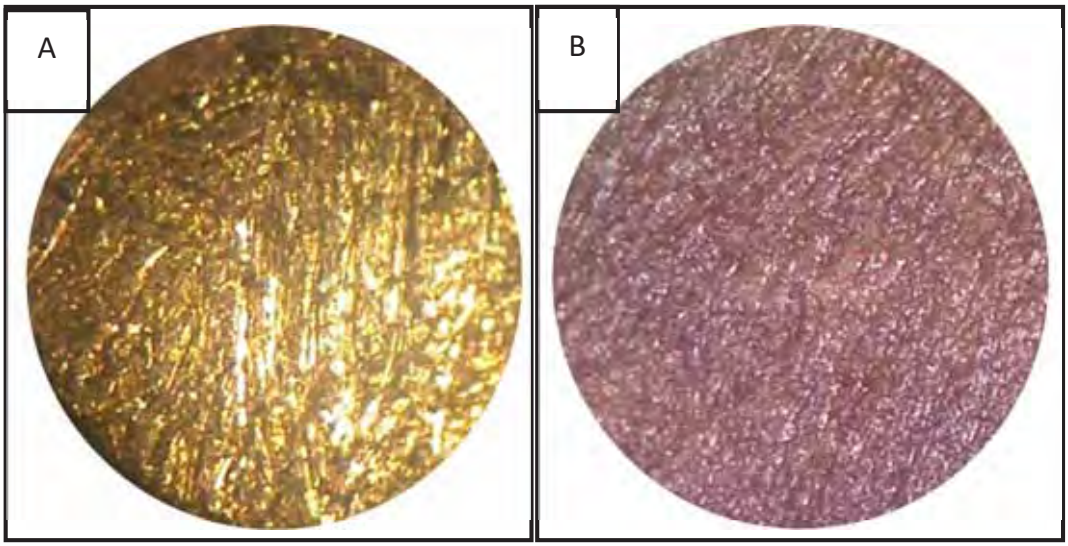


Fig. 2: The electrode surface image before (A) and after (B) coating a mixture of FA and paraffin (Magnification 45X)

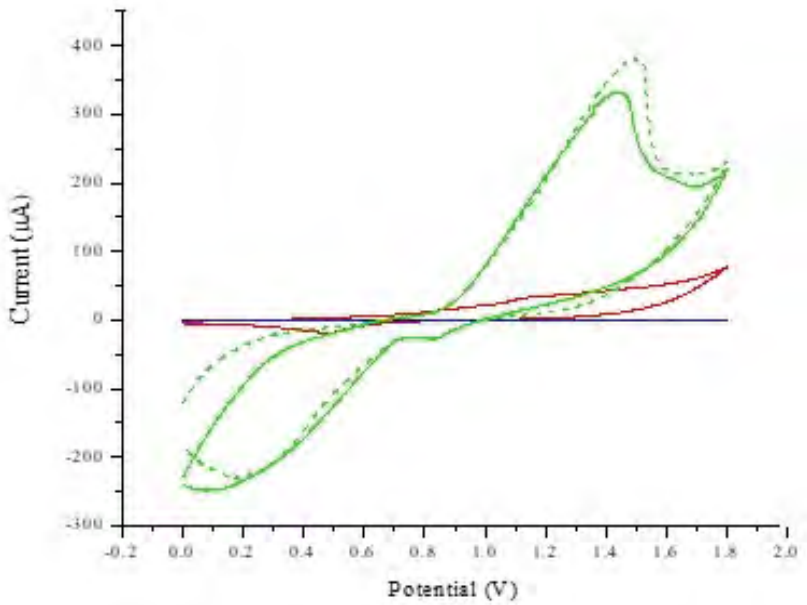


Fig. 3: Cyclic voltammogram of GE (green), P-GE (blue), and FA-GE (red) at 1 mM formaldehyde in 0.1 N HCl (solid line) and blank (dashes line)

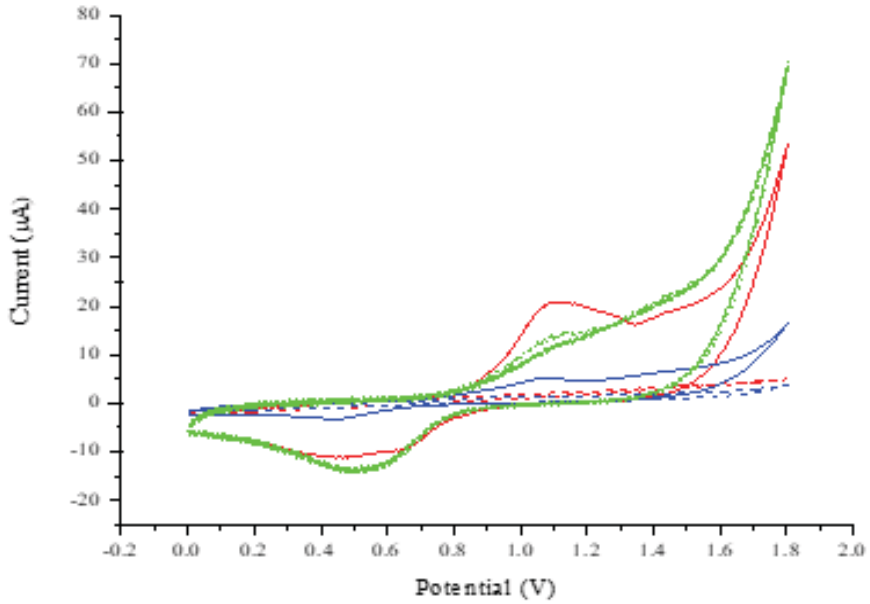


Fig. 4: Cyclic voltammogram of FA-GE to blank (dashed line) and 1 mM Formaldehyde (solid line) in pH 1 (red), pH 7 (blue), and pH 13 (green).

for P-GE (blue), which did not show any response to formaldehyde at all because paraffin is a non-conductive compound that functions as a binder in this experiment. Concurrently, FA-GE (red) exhibits a remarkable response to solid formaldehyde, highlighted by a current peak, but does not respond to the blank (dashed) (inset). The oxidation current peak is at a potential of +1.13V, and the reduction current peak is at a potential of +0.79 V. So, it can be concluded that FA is electrochemically active toward formaldehyde.

The effect of pH measurement

Fig. 4 shows 1 mM of formaldehyde by FA-GE in various pH measurements. The electrode shows no response against formaldehyde at pH 13 (green) because the blank voltammogram (dash line) overlaps with the formaldehyde voltammogram (solid line). This suggests that at this pH, formaldehyde does not undergo any oxidation or reduction reactions. On the other hand, there is a different response between the blank voltammogram (dash line) and a formaldehyde voltammogram (solid line) to formaldehyde at pH 7 (blue) and pH 1 (red), but the oxidation and The findings indicate that FA-GE exhibits optimal performance against formaldehyde at a pH of 1. The abundance of H^+ ions is likely instrumental in catalyzing the electrooxidation reaction. Consequently, pH 1 will be utilized in future experimental procedures.

The effect of scan rate

The voltammograms of 1 mM formaldehyde by FA-GE at various scan rates (50 – 350 mV/s) were shown in Fig. 5A. The current peak increases along with the scan rate using Randles-Sevcik Eq. 1 (Lee *et al*., 2024):

$$ip = (2.69\times105)\, n^{3/2} A C D^{1/2} v^{1/2} \quad (1)$$

Where, ip is the peak current, n is the number of electrons, A is the electrode area, C is the concentration, D is the diffusion coefficient, and v is the potential scan rate. Fig. 5B shows that the peak current for the anodic oxidation is proportional to the square root of the scan rate with the linear regression equation anodic peak current (Ipa) (microampere (μA)) = 6.967x + 37.355 (R^2 = 0.9925). A corresponding calculation has likewise been executed for the cathodic current. Fig. 5C shows that the peak current for the cathodic reduction is proportional to the square root of the scan rate with the linear regression equation cathodic peak current (Ipc) (μA) = -3.9959x + 21.114 (R^2 = 0.9916. The results indicated that the process that occurred at the electrodes was diffusion-controlled. The analysis revealed that the

Fig. 5:

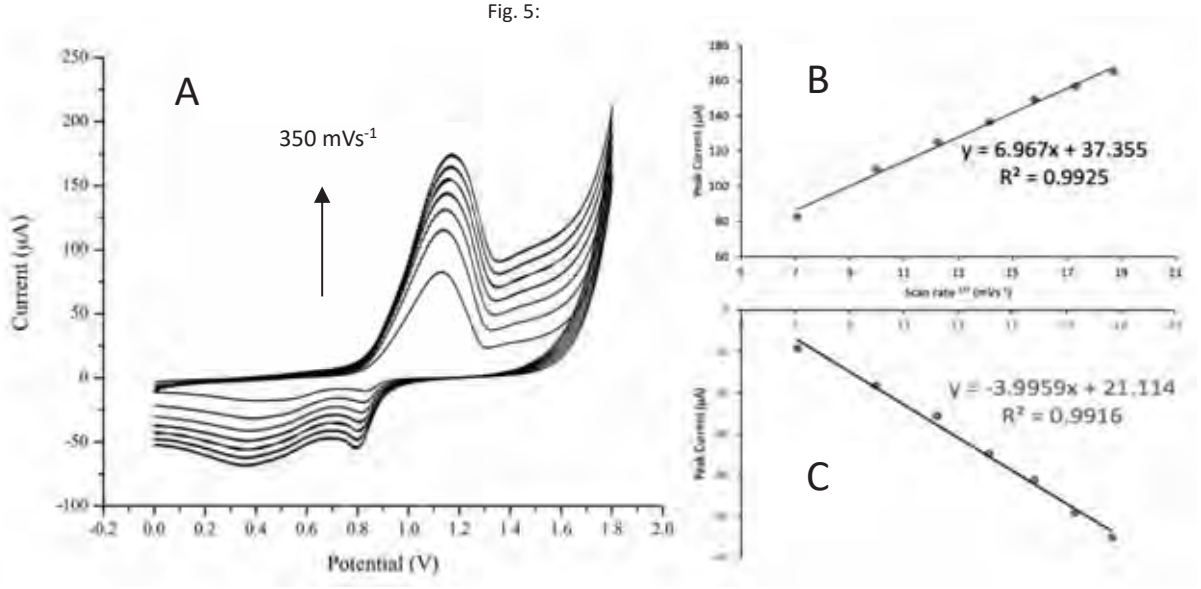


Fig. 5: Voltammograms of 1 mM Formaldehyde on FA-GE with scan rates 50, 100, 150, 200, 250, 300, and 350 mV/s (A). The plot of peak anodic current at +1.13 V vs. Square root of the scan rate (B). The plot of peak/ cathodic current at +0.79 V vs. Square root of the scan rate (C).

mechanisms at the electrodes were predominantly controlled by diffusion processes. Eq. 2 presents the reaction mechanism, highlighting the various reactions that may occur on the FA-GE surface (Wei *et al*., 2024):

$$CH_2O \rightleftarrows CH_2O_2 \quad (2)$$

This reaction represents a reversible oxidation-reduction process of formaldehyde. During this process, formaldehyde is oxidized to generate formic acid, which can then be reduced back to its original form, formaldehyde.

Calibration Curve for formaldehyde detection using FA-GE

Fig. 6A is a voltammogram of formaldehyde using FA-GE in various concentrations ranging from 0.1 to 3 mM. It is evident that as the concentration of formaldehyde increases, the anodic current peak also shows an upward trend. It shows the Ipa at +1.13 V and the Ipc at +0.79 V. Both Ipa and Ipc provide a linear relationship but with the opposite direction to the increase in concentration. It gives a linear equation of i = 15.987c + 7.3901 for the anodic current with R^2 = 0.9984 (Fig. 6B) and i = -5.5115c - 3.1776 for the cathodic current with R^2 = 0.9939 (Fig. 6C). While both can be utilized for quantitative analysis, the oxidation current offers enhanced sensitivity over the reduction current. The sensitivity of the oxidation and reduction currents is 20.365 microampere millimolar per square millimeter (µA mM/mm^2) and 7.021 µA mM/mm^2, respectively.

The LOD calculation in this report uses the formula 3σ/m, where m is the slope of the line, and σ is the blank standard deviation for five measurements. The levels of detection for the oxidation and reduction currents are recorded at 4.07 µM and 15.14 µM, respectively. The performance of FA-GE compared to other electrodes can be found in Table 2. The detection limits established in this study are the most minimal in relation to the other electrodes evaluated.

Selectivity, repeatability, and reproducibility

The voltammograms depicted in Fig. 7 represent various compounds that may exist in the sample when assessing formaldehyde through FA-GE. The identified compounds are methanol, ethanol, glycerol, and glucose (Nurlely *et al*., 2021; Teišerskytė *et al*., 2021). The voltammograms of ethanol, glycerol, and glucose show no interference against formaldehyde. Simultaneously, the capacitive current response recorded for methanol measurements was significantly high. The relatively high capacitive current response recorded for the methanol measurement reflects the interaction between the

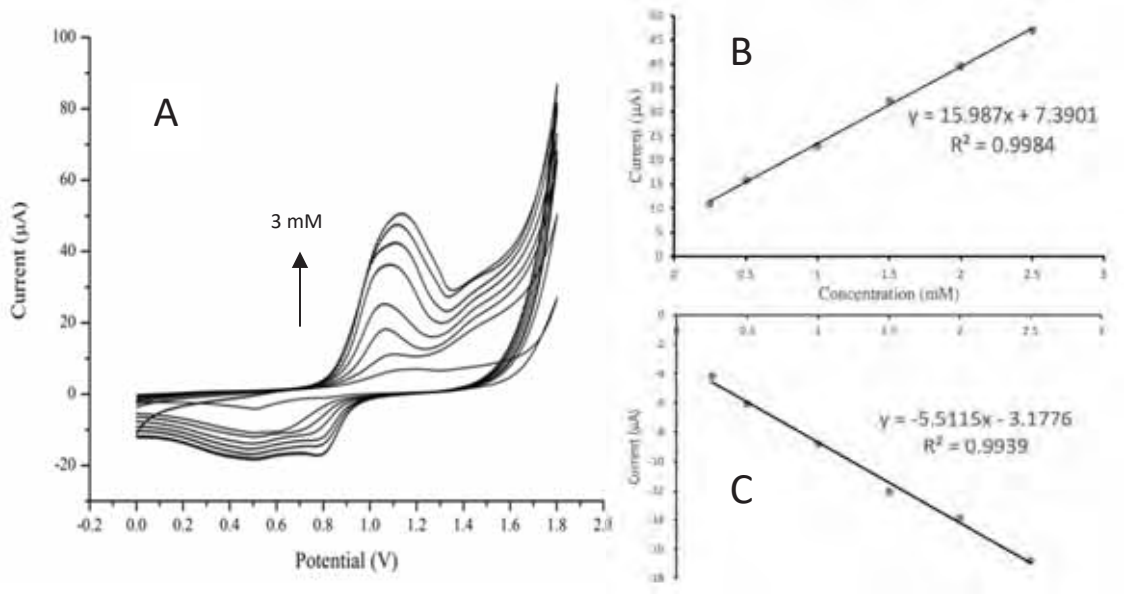


Fig. 6: Cyclic voltammogram of FA-GE in various formaldehyde concentrations (0.1–3 mM) in HCl 0.1 N (A). The calibration curve for anodic current at +1.13 V (B). The calibration curve for cathodic current at +0.79 V (C)

Table 2: Performance of selected electrodes to formaldehyde determination

Measurement technique	Electrodes	Range concentrations (mM)	LOD (μM)	Sensitivity (μA mM/cm^2)	Sources
Chronoampero metric	CuO/Cu/TNAs	0.065 – 7.80	25	814.0	Zhang *et al.*, 2020
Linear sweep voltammetry	Ni(OH)2/rGO/GCE	0.1– 100	60	47.53	Li *et al.*, 2022
CV	CuO/Cu_2O/CILE	0.1 – 110	10	186.0	Momeni and Sedaghati, 2018
CV	GPE/ZnO NPs	0 – 100	18	281.69	Wicaksono *et al.*, 2022
CV	FA-GE	0.1 – 3	4.07	2036.5	The current study

electrode surface and methanol molecules in the solution, resulting in a current increase that does not involve a distinct electrochemical reaction. However, the absence of an oxidation peak at a potential of +1.13 V and a reduction peak at a potential of +0.79 V indicates that a significant electron transfer process does not occur in this potential range. The underlying causes of this phenomenon may include the electrode's lack of capability to catalyze the methanol oxidation-reduction reaction, the presence of a substantial kinetic barrier, or electrolyte conditions that do not facilitate optimal electrochemical reactions. In addition, the interaction between methanol and the electrode may be more adsorptive than electrocatalytic, resulting in a dominant capacitive current compared to the faradaic current expected in oxidation and reduction processes. Analyzing formaldehyde mixtures with all conceivable interference compounds can help clarify their influence.

The current peaks of individual compounds and formaldehyde mixtures, as determined by FA-GE, are depicted in Fig. 8. The peak anodic current value was measured at a potential of +1.13V (Fig. 8A), and the

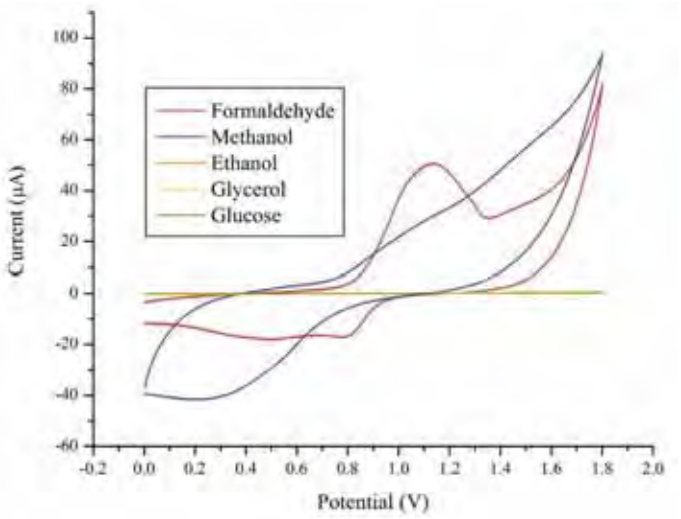


Fig. 7: Cyclic voltammogram of various compounds (3 mM in 0.1 N HCl) using FA-GE

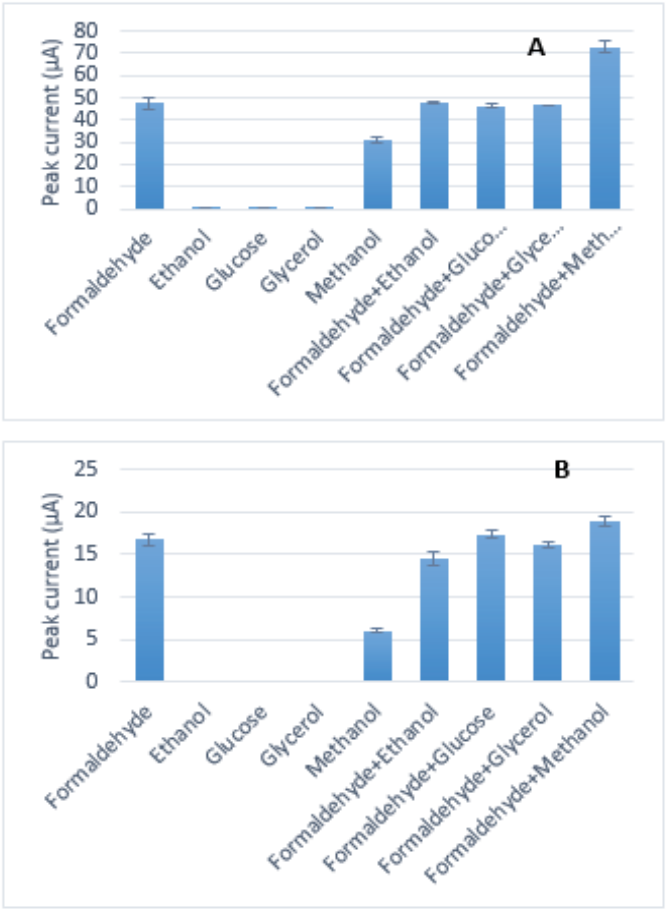


Fig. 8: Oxidation peak current (A) and reduction peak current (B) of various compounds And formaldehyde mixtures (3 mM in 0.1 N HCl) by FA-GE

cathodic current was measured at +0.79V (Fig. 8B). Aside from the methanol mixture, formaldehyde measurements at the anode current are largely unaffected by significant interference, while no such interference is noted at the cathode current. The mixture of methanol-formaldehyde shows a current that was not significantly different from the formaldehyde current alone at the cathodic current. This implies that the assessment of formaldehyde is devoid of interference. Therefore, it was concluded that FA-GE displays significant selectivity towards formaldehyde.

Using FA-GE, 1 mM Formaldehyde was measured 3 times, each repeated 5 times. The result is presented in Table 3. The analysis of variance (ANOVA) single-factor test is conducted at a 95% confidence level utilizing Microsoft Excel. The F-value of the calculation is lower than the F critical value, meaning no significant difference in variance between measurements. The calculated least square difference (LSD) stands at 1.44169, which signifies that there are no substantial differences among the measurements. This finding confirms that the electrode has a high level of repeatability.

Additionally, five separate electrodes were utilized to evaluate 1 mM formaldehyde, with each electrode conducting five measurements. The results obtained are presented in Table 4. Analogous calculations are utilized to evaluate the effectiveness of the electrodes. The F value is lower than the F critical value, meaning no significant difference variance between electrodes. Moreover, the LSD value is greater than the disparity between the maximum and minimum average values of the measurements, suggesting that there is no notable difference in the readings from the electrodes. Therefore, it can be concluded that the reproducibility fabrication of the electrodes is good.

Performance FA-GE versus UV-Vis spectrophotometric Nash method for real sample measurement

The method used in this work was compared to the standard method. The standard procedure for assessing formaldehyde concentration in samples is primarily based on the UV-Vis spectrophotometry technique (Qian *et al*., 2023). Formaldehyde content in real samples (fish) was measured using FA-GE and Nash methods. The result is shown in Table 5. The

Table 3: Peak current 1 mM Formaldehyde measurement using one FA-GE

Number of cyclic	Current at +1.13 V (μA)		
	First Measurement	Second Measurement	Third Measurement
1	32.2357	33.08165	33.08592
2	31.97299	31.91104	33.11371
3	33.76954	31.48803	32.2357
4	30.28746	31.15476	31.55215
5	30.56305	32.17165	31.19326
Mean	31.76575	31.96143	32.23615
F value	0.25507		
F critical value	3.88529		
LSD	1.44169		

Table 4: Peak current 1 mM formaldehyde measurement using five FA-GE

Measurement	FA-GE				
	1	2	3	4	5
1	35.7086	34.2529	34.0576	34.6375	34.6802
2	31.1707	32.6874	32.8827	31.4209	33.0231
3	30.1758	31.1310	32.0984	30.3375	32.4615
4	30.1575	30.0079	28.2440	29.4739	31.1798
5	29.8950	28.8055	27.2491	28.7415	29.3518
Mean	31.4215	31.3769	30.9064	30.9223	32.1393
F value	0.21838				
F critical value	2.86608				
LSD	3.16980				

Table 5: Performance of FA-GE and Nash method for determining formaldehyde content in fish samples

Sample	Method	The concentration of formaldehyde (mg/L)	t value
Fish	Nash method	3.97 ± 0.098	1.47
	FA-GE	4.21 ± 0.180	

t-critical value = 4.303 (P = 0.05)

mean of the two methods is calculated using the t-test: paired two samples for mean using Microsoft Excel at P = 0.05. Since the t value derived is below the critical t value, it suggests that there is no significant difference observed for both electrodes. This indicates that FA-GE can be used as an alternative method for formaldehyde analysis in place of the Nash Method. Compared to the Nash method, FA-GE presents various advantages, notably in efficiency, affordability, and simplicity of use. FA-GE is more economical because it does not require complex or expensive reagents, so it can reduce operational costs in the long term. Moreover, this method allows for a more efficient measurement process and does not involve elaborate sample preparation, making it more accessible for users to perform analyses. In terms of speed, FA-GE allows the detection of formaldehyde in a shorter time than the Nash method, which usually requires an additional chemical reaction step before measurements are made. One of the key advantages is the versatility of FA-GE-based sensors in field applications. They can function without the requirement for bulky laboratory equipment, thereby increasing their practicality for monitoring in a variety of environmental conditions.

CONCLUSION

A novel FA-GE has been developed for formaldehyde detection, utilizing FA that contains amino acids, such as glycine, lysine, and histidine, which react with formaldehyde. This cutting-edge sensor reveals remarkable sensitivity and low detection limits in acidic settings, exhibiting significant formaldehyde signals compared to alkaline and neutral environments. The FA-GE electrode showed a linear detection range of 0.1 to 3 mM, with a detection limit of 4.07 µM and a sensitivity of 20.365 µA mM^{-1} mm^{-2}. The application of this method to fish samples yielded results that were on par with the traditional Nash method, while also providing the benefit of eliminating the need for additional reagents. Albumin, a versatile protein found in various organisms, including humans, plants, and animals, has diverse applications in fields such as drug delivery, wound healing, corrosion inhibition, and sensor technology. The potential of FA from *Channa striata* as a sensor material has been explored in this study, leading to the fabrication of the FA-GE by immobilizing fish albumin on a gold electrode. Demonstrating effectiveness in acidic conditions, this electrochemical sensor offers a viable alternative for the detection of formaldehyde, with significant applications in food safety and environmental monitoring. Formaldehyde sensors find significant applications in various important fields. Within the food industry, these techniques are implemented to assess and ensure the safety of food products, effectively preventing the unauthorized use of formaldehyde for preservation purposes. In the environmental sector, these sensors help monitor formaldehyde levels in air and water, contributing to pollution control and public health safety. Furthermore, in industrial environment, the use of formaldehyde sensors is essential for ensuring safety standards are met by continuously monitoring formaldehyde emissions from production activities, which helps protect employees from the risks associated with this toxic chemical. These versatile applications highlight the critical role of formaldehyde sensors in ensuring safety and compliance across different industries. Furthermore, in the ecological field, formaldehyde sensors are vital for assessing the impact of formaldehyde pollution on ecosystems. The detection and monitoring of formaldehyde levels in natural habitats by these sensors facilitate the identification of pollution sources and the assessment of mitigation strategies, thereby contributing to the safeguarding of biodiversity and the stability of ecological systems.

AUTHOR CONTRIBUTIONS

T.P.H. Hutapea conducted the literature review, designed the experiments, analyzed and interpreted the data, and prepared and edited the manuscript. Suprapto carried out the experiments and literature review, compiled the data, and contributed to manuscript preparation. M.Y. Syahputra assisted with

manuscript preparation and project administration. F. Kurniawan conducted the literature review, designed the experiments, analyzed and interpreted the data, and prepared and edited the manuscript.

ACKNOWLEDGEMENT

This work has been performed under the scheme of Keilmuan ITS [contract number: 957/PKS/ITS]

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral concerning jurisdictional claims with regard to published maps and institutional affiliations.

ABBREVIATIONS

%	Percent
^0C	Degrees Celsius
µA	Microamprere
µA mM/mm²	Microampere millimolar per square millimeter
µM	Micromolar
Ag/AgCl	silver/silver chloride
ANOVA	Analysis of variance
BSA	Bovine serum albumin
cm	Centimeter
CV	Cyclic voltammetry
FA	Fish albumin
FA-GE	Fish albumin-modified gold electrodes
GE	Gold electrodes
HSA	Human serum albumin
HCl	Hydrochloride acid
Ipa	Anodic peak current
Ipc	Cathodic peak current
KCl	Potassium chloride
LOD	Limit of detection
LSD	Least square different
M	Molar
mm	Millimeter
mM	Millimolar
mV/s	Millivolt per second
N	Normality
nm	Nanometer
OVA	Ovalbumin
P-GE	Paraffin-modified gold electrodes
pH	Potential of hydrogen
V	Volt

REFERENCES

Dorieh, A.; Farajollah Pour, M.; Ghafari Movahed, S.; Pizzi, A.; Pouresmaeel Selakjani, P.; Valizadeh Kiamahalleh, M.; Hatefnia, H.; Shahavi, M. H.; Aghaei, R., (2022). A review of recent progress in melamine-formaldehyde resin based nanocomposites as coating materials. Progress Org. Coat., 165: 106768.

Fadeyibi, M.; Sawyerr, O.H.; Opasola, A.O.; Ishola, O.A., (2024). Comparative evaluation of disinfectant effectiveness on clinical bacterial isolates in a disk diffusion study. Afr. J. Health Saf. Environ., 5. 57–65 **(9 pages).**

Hermanto, D.; Ismillayli, N.; Muliasari, H.; Wirawan, R.; Kamali, S.R., (2023). Silver-based plasmonic nanoparticles for biosensor organophosphate pesticides using a single film containing acetylcholinesterase/choline oxidase. Global J. Environ. Sci. Manage., 10(1): 39-50 **(12 pages).**

Hou, X.; Jiang, Z.; Wang, X.; Sun, X.; Wang, Y.; Liu, W.; Ding, L., (2023). Synthesis of hollow molecular imprinting nanoparticles based on polyethylenimine and boronate affinity for selective extraction of ovalbumin. J. Chromatogr. A, 1705: 464181.

Hutapea, T.P.H.; Madurani, K.A.; Syahputra, M.Y.; Hudha, M.N.; Asriana, A.N., Suprapto; Kurniawan, F., (2023). Albumin: source, preparation, determination, applications, and prospects. J. Sci.: Adv. Mater. Devices, 100549.

Hutapea, T.P.H.; Muliyadi, M.; Rukisah, R.; Suprapto, S.; Kurniawan, F., (2024). Development of a chromium (VI) biosensor using silver-modified milkfish (chanos chanos) gelatin and carbon electrodes. Eurasian J. Phys. Funct. Mater., 8: 1–19 **(19 pages).**

Hutapea, T.P.H.; Suprapto; Kurniawan, F., (2022). Extraction of dissolved protein of channa striata from tarakan, north borneo as a source of fish serum albumin. IOP Conference Series: Earth Environ. Sci., 1083(1): 012080.

Jia, M.; Shao, L.; Jiang, J.; Jiang, W.; Xin, F.; Zhang, W.; Jiang, M., (2024). Mitigating toxic formaldehyde to promote efficient utilization of C1 resources. Crit. Rev. Biotechnol., 1–13 **(13 pages).**

Kaseem, M.; Ko, Y.G., (2021). A novel hybrid composite composed of albumin, WO3, and LHDs film for smart corrosion protection of Mg alloy. Comp. Part B: Eng., 204: 108490.

Kiswandono, A.A.; Ningsih, N.; Sindiani, A.V.; Rinawati; Qudus, H.I., (2024). Phenol solutions recovery as water pollutants with eugenol cross-linked diallyl phthalate using supported liquid membrane. Global J. Environ. Sci. Manage., 10(SI): 53-70 **(18 pages).**

Lee, Y.Y.; Sriram, B.; Wang, S.F.; Stanley, M.M.; Lin, W.C.; Kogularasu, S.; Chang-Chien, G.P.; George, M., (2024). Eco-innovative electrochemical sensing for precise detection of vanillin and sulfadiazine additives in confectioneries. Appl. Surf. Sci. Adv., 20: 100584.

Li, N.; Xu, Z.; Chen, Y.; Deng, W.; Qin, T.; Lv, T.; Wang, L.; Liu, B., (2024). A novel albumin-based supramolecular biosensor for ratiometric on-site determination of buprofezin. Sens. Actuators, B., 413. 135823.

Li, S.; Li, M.; Yang, H.; Shao, J.; Meng, Z., (2022). Facile synthesis of flower-like $Ni(OH)_2$/rGO nanocomposite as sensitive electrochemical sensor for formaldehyde detection. Int. J. Electr. Sci., 17(7): 22079.

Lian, X.; Zhang, M.; Sun, X.; Song, C.; Yuan, H.; Guo, L.; Li, X., (2021). Online real time determination of free formaldehyde content during polymerization process of phenolic resin by NIR spectra and a modeling-free method. Poly. Test., 93: 106584.

Liu, D.; Zhao, S.; Jiang, Y.; Gao, C.; Wu, Y.; Liu, Y., (2023). Biocompatible dual network bovine serum albumin-loaded hydrogel-accelerates wound healing. Euro. Poly. J., 185: 111820.

Momeni, S.; Sedaghati, F., (2018). CuO/Cu_2O nanoparticles: a simple and green synthesis, characterization and their electrocatalytic performance toward formaldehyde oxidation. Microchem. J., 143: 64–71 **(8 pages).**

Nayak, S.; Nayak, P.; Saha, S.; Patnaik, L.; Nayak, S.; Pradhan, S.P.; Sharma, S.N.; Muduli, N., (2024). Formaldehyde as preservative for fish and seafood: a boon or a bane. Environ. Qual. Manage., 34: e22357.

Nurfaidah, N.; Asikin, A.N.; Kasmiati, K.; Angraeni, A. (2024). Amino acid profile and potential utilization purposes of albumin from four types of freshwater fish in makassar, south sulawesi, indonesia. Biodiversitas, 25: 4199-4207 **(9 pages).**

Nurlely; Ahmad, M.; Yook Heng, L.; Ling Tan, L., (2021). Potentiometric enzyme biosensor for rapid determination of formaldehyde based on succinimide-functionalized polyacrylate ion-selective membrane. Measurement, 175: 109112.

Padmalaya, G.; Vardhan, K.H.; Kumar, P.S.; Ali, M.A.; Chen, T.W., (2024). Expression of concern: a disposable modified screen-printed electrode using egg white/ZnO rice structured composite as practical tool electrochemical sensor for formaldehyde detection and its comparative electrochemical study with chitosan/ZnO nanocomposite. Chemosphere, 356: 141999.

Qian, J.; Fan, L.; Yang, J.; Feng, J.; Gao, N.; Cheng, G.; Pu, W.; Zhou, W.; Cai, T.; Li, S.; Zheng, P.; Sun, J.; Wang, D.; Wang, Y. (2023). Directed evolution of a neutrophilic and mesophilic methanol dehydrogenase based on high-throughput and accurate measurement of formaldehyde. Synth. Syst. Biotechnol., 8: 386–395 **(10 pages).**

Rizki, W.O.S.; Komariah, S.; Andini, D.G.T.; Simbara, A.T.; Ratnaningsih, E.; Hertadi, R., (2024). Physicochemical characterization of biodegradable polymer polyhydroxybutyrate from halophilic bacterium local strain Halomonas elongata, Global J. Environ. Sci. Manage., 10(3): 1117-1132 **(16 pages).**

Samimi, M., (2023). Efficient biosorption of cadmium by Eucalyptus globulus fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 **(12 pages).**

Sánchez, L.L.; Miralles, P.; Salvador, A.; Merino-Sanjuán, M.; Merino, V., (2021). In vitro skin penetration of bronidox, bronopol and formaldehyde from cosmetics. Regul. Toxicol. Pharmacol., 122: 104888.

Soedjanaatmadja, U.M.; Adnani, N.; Abiyyi. W.; Rachman, S.D.; Gaffar, S.; Ishmayana, S.; Hardiyanto, A., (2021). Albumin, as a therapeutic protein: potential source, application, isolation and purification. Int. J. Res. Pharm. Sci., 12: 1922–1931 **(10 pages).**

Soltanpour, Z.; Mohammadian, Y.; Fakhri, Y., (2022). The exposure to formaldehyde in industries and health care centers: a systematic review and probabilistic health risk assessment. Environ. Res., 204, 112094.

Suprihatin, S.; Indrasti, N.S.; Prasetya, H.; Agustina, L.; Yulistika, E., (2024). Nine circular strategy approach for the sustainable management of waste in the palm oil industry. Global J. Environ. Sci. Manage., 10(SI): 89-104 **(16 pages).**

Teišerskytė, V.; Urbonavičius, J.; Ratautas, D., (2021). A direct electron transfer formaldehyde dehydrogenase biosensor for the determination of formaldehyde in river water. Talanta, 234: 122657.

Tiwari, R.; Sethiya, N.K.; Gulbake, A.S.; Mehra, N.K.; Murty, U.S.N.; Gulbake, A., (2021). A review on albumin as a biomaterial for ocular drug delivery. Int. J. Biol. Macromol., 191: 591–599 **(9 pages).**

Torun, S.B., (2022). Investigation of the properties of fiberboards made from microcrystalline cellulose and antimony trioxide added melamine formaldehyde adhesive. Int. J. Adhes. Adhesives., 113: 103084.

Wei, Y.; Zhang, X.; Qing, S.; Wang, H., (2024). Reaction mechanism of pyrolysis and combustion of methyl oleate: a reaxff-md analysis. Energies, 17: 3536.

Wicaksono, W.P.; Fadilla, N.I.; Zamar, A.A.; Fadillah, G.; Anugrahwati, M.; Anas, A.K.; Kadja, G.T.M., (2022). Formaldehyde electrochemical sensor using graphite paste-modified green synthesized zinc oxide nanoparticles. Chem. Comm., 143: 109729.

Zhang, S.; Wen, X.; Long, M.; Xi, J.; Hu, J.; Tang, A., (2020). Fabrication of $CuO/Cu/TiO_2$ nanotube arrays modified electrode for detection of formaldehyde. J. All. Comp., 829: 154568.

AUTHOR (S) BIOSKETCHES

Hutapea, T.P.H., Ph.D., Assistant Professor, Fisheries Product Technology Department, Faculty of Fishery and Marine Science, University of Borneo Tarakan, North Borneo, Indonesia.
▪ Email: *hutapea@borneo.ac.id*
▪ ORCID: 0000-0003-0154-2680
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57194337088
▪ Homepage: https://www.ubt.ac.id/fakultas/fakultas-perikanan-dan-ilmu-kelautan/program-studi-teknologi-hasil-perikanan/

Suprapto, Ph.D., Associate Professor, Chemistry Department, Institute Teknologi Sepuluh Nopember, Surabaya, East Java, Indonesia.
▪ Email: *suprapto@chem.its.ac.id*
▪ ORCID: 0000-0002-1490-0726
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 55626183800
▪ Homepage: https://scholar.its.ac.id/en/persons/suprapto-2

Syahputra, M.Y., [1]Ph.D. Candidate, Saga University Japan. [2]Chemistry Department, Institut Teknologi Sepuluh Nopember, Surabaya, East Java 60111 Indonesia.
▪ Email: *23808291@edu.cc.saga-u.ac.jp*
▪ ORCID: 0000-0003-6232-839X
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57190936674
▪ Homepage: https://www.bioelectrochem.chem.saga-u.ac.jp/en/member

Kurniawan, F., Ph.D. Professor, Chemistry Department, Institute Teknologi Sepuluh Nopember, Surabaya, East Java, Indonesia.
▪ Email: *fredy@its.ac.id*
▪ ORCID: 0000-0002-9777-0989
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 25627866400
▪ Homepage: https://scholar.its.ac.id/en/persons/fredy-kurniawan

HOW TO CITE THIS ARTICLE

Hutapea, T.P.H.; Suprapto; Syahputra, M.Y.; Kurniawan, F., (2025). Green chemistry approach to Formaldehyde detection using fish albumin-modified gold electrodes. Global J. Environ. Sci. Manage., 11(2): 791-804.

DOI: 10.22034/gjesm.2025.02.23

URL: https://www.gjesm.net/article_721470.html

Global J. Environ. Sci. Manage. 11(2): 805-824, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

CASE STUDY

Mathematical model of the territorial bioecological coefficient to evaluate the progress of the sustainable development goal

R. Zapata Stacey[1], D. Pinto Osorio[1], C.A. Rodríguez Nieto[2,*], M. Machado Penso[3]

[1] *Department of Civil and Environmental Engineering, Universidad de la Costa, Barranquilla, Colombia*

[2] *Department of Natural and Exact Sciences, Universidad de la Costa, Barranquilla, Colombia*

[3] *Department of Planning and Land Use Planning, School of Architecture, Universidad Tecnológica Metropolitana, Chile*

ARTICLE INFO

Article History:
Received 22 November 2024
Revised 26 January 2025
Accepted 09 March 2025

Keywords:
Bioecological coefficient
Sustainable development goal (SDG)
Territory

ABSTRACT

BACKGROUND AND OBJECTIVES: The geographic location of the department of Atlántico makes it highly vulnerable to climate effects, placing it in an environmental risk zone within the Colombian Caribbean region. This scenario requires the development of initiatives that align with the Sustainable Development Goals, and climate action, ratified at the United Nations Conference on Climate Change. It is imperative for governmental organizations to engage in sustainable development through the execution of initiatives that respond to the climate challenges present in the region. These initiatives are designed to secure the survival, promote economic growth, and enhance environmental sustainability for the residents of every municipality in the departments. The objective of this study was to create a territorial bioecological coefficient model designed to measure advancements in development objectives and goals grounded in natural factors. Additionally, the model aims to assess environmental elements and ecosystem resources while considering the impacts of climate change, particularly within the Department of Atlántico, Colombia.
METHODS: This model will allow for more effective anticipation of climate adaptation strategies, correlating the sustainable development goals with the progress established by the United Nations. The integration of these components will lead to more cohesive planning that aligns with global objectives, thereby optimizing both resources and efforts. This will facilitate the identification of priority areas for climate action and promote collaboration between different actors. Additionally, the model will support the tracking and evaluation of progress in achieving climate resilience, encouraging accountability and the adaptation of strategies to meet emerging challenges, which will ensure a holistic response to climate change and its consequences.
FINDINGS: This innovative approach addresses a significant gap, as there is currently no specific mathematical model to measure this coefficient. This tool would play a critical role in assessing ecosystem services and resources, supporting the design of territorial strategies that are tailored to climate change, consistent with sustainable development goals, and reinforcing local resilience, thus encouraging sustainable development. This approach promotes the adoption of sustainable territorial strategies in the face of climate change, which implies strategic coordination between academia, the productive sector, grassroots organizations, territory and local government. A non-compliance rate has been identified at the municipal and local level of sustainable development goal-13, with a percentage of climate actions of 85.60 percent in Usiacurí, 86.23 percent in Puerto Colombia and 84.50 percent in Suan.
CONCLUSION: The territorial bioecological coefficients model developed for the Atlantic is presented as an innovative tool that allows the evaluation of ecosystem resources and progress towards the sustainable development goals. This method fosters the integration of sustainable regional strategies as a response to the impacts of climate change.

DOI: 10.22034/gjesm.2025.02.24

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
42

NUMBER OF FIGURES
3

NUMBER OF TABLES
10

*Corresponding Author:
Email: *crodrigu79@cuc.edu.co*
Phone: +301 676 2709
ORCID: 0000-0001-9922-4079

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Sustainable development (SD) is characterized by its primary purpose of improving the quality of life of all people around the world, including regions, countries, cultures, etc., considering both current and future generations (Dernbach and Cheever, 2015; Husamah *et al*., 2022; Li *et al*., 2024; Mensah, 2019). SThe concept of SD includes various objectives designed to support communities, and it is imperative for every country to ensure that its citizens can fulfill their needs sustainably (Fábregas Villegas *et al*., 2024; Jauhari *et al*., 2025; Onoshakpokaiye, 2023; Teweldebrihan and Dinka, 2024). The realization of this objective hinges on key factors, including economic growth and equity, social development, the preservation of natural resources (environmental protection), and the establishment of good governance along with the execution of State policies (Chan *et al*., 2021; Eilks, 2015; Jiménez-Bedoya *et al*., 2024; Liu *et al*., 2021). There are 17 sustainable development goals (SDGs). SDG-13 focuses on climate action, SDG-6 on clean water, SDG-7 on clean energy, SDG-11 on sustainable cities, SDG-14 on marine life, SDG-15 on terrestrial ecosystems, and SDG-17 on partnerships to achieve these goals (UN, 2015). Regarding SDG-13, extensive research has demonstrated its relevance to climate change and its appropriate use for teaching in various subjects (Gómez, 2018; Hroub et al., 2025; Morote and Olcina, 2023; Rocasolano, 2019; Turró-Noa, 2023). Further exploration of climate change has highlighted that other research investigates its repercussions on different ecosystems, such as water systems, agricultural practices, and land use in regions that are at risk (Imalda and Hidayat, 2024; Jiménez-Bedoya *et al*., 2024; Teweldebrihan and Dinka, 2024). Citing some studies, Gupta and Vegelin (2016) analyzed whether the SDGs prioritize the concerns of the poor and their ecological problems or whether the SDG agenda risks being stifled by the ecological and developmental interests of the rich, focusing on economic growth at the expense of other aspects. Behera *et al.* (2024) examined the crucial role of renewable energy use, green finance, and political stability in achieving SDG-13 by reducing carbon dioxide (CO_2) emissions in emerging economies from 1990 to 2021. There is a prevailing assumption that the risks of climate change cannot be effectively mitigated unless CO_2 emissions are decreased, as they significantly contribute to its global consequences. Meanwhile, Liu *et al.* (2023) investigated how carbon sequestration services in ecosystems support progress on the SDGs. Numerous studies highlight the importance of sustainable development, particularly in areas with varied environmental and socioeconomic conditions (Nkaizirwa *et al*., 2021; Nketiah *et al.,* 2024; Tu *et al*., 2017). These articles explore various strategies focused on the environment, society and economy, with the aim of consolidating sustainability (Eilks, 2015). Their analysis highlights how professional, technical, educational initiatives linked to teaching and learning and technological initiatives play a fundamental role in promoting SD (Gündüz, 2017). Aligned with SDG-4 (Nkaizirwa *et al*., 2021), these educational methods strive to ensure that, by 2030, students develop the theoretical and practical skills necessary to promote environmental sustainability. This encompasses sustainable lifestyles (SDG-15), human rights and culture of peace (SDG-16), gender equality (SDG-5), zero hunger (SDG-2), global citizenship and appreciation of cultural diversity (SDG-11) (Wang, 2016). A key element highlighted is international cooperation (SDG-17), which drives strategic alliances to achieve global goals (Maashi *et al*., 2022). Collaborative efforts across regions and the sharing of knowledge are essential for addressing common sustainability issues. They enhance public policies and global understanding of local issues, fostering equitable climate actions (SDG-13). From the science, technology, engineering and mathematics (STEM) perspective, climate change serves as a key strategy to integrate sustainability into the SDGs (Álvarez-Ariza and Olatunde-Aiyedun, 2024). This method allows regions to address the challenges of climate change, presenting environmental solutions in a manner that is both innovative and resilient. Through project-centered methodologies, collaboration between disciplines is promoted and techniques are implemented that develop an ethical and critical awareness of sustainability, strengthening the skills of future generations (Gökel and Dağlı, 2017). A significant element involves refining assessments of sustainable pro-environmental attitudes and behaviors, as gaining insight into how people view and respond to environmental issues is critical for developing effective interventions (Nkaizirwa *et al*., 2021). Previous studies highlight the

need to update assessment tools to better understand the relationship between human actions and the environment. This will help prioritize interventions and promote sustainability. Additionally, they emphasize the training of leaders in various sectors using digital tools and hybrid learning methodologies (Gökel and Dağlı, 2017; Tu *et al*., 2017). By merging digital platforms with direct engagement, these strategies successfully enhance the teaching sustainability and land use planning. The examples presented demonstrate how these methodologies strengthen local governments and communities, promoting fundamental knowledge about environmental management and equity principles adapted to specific contextual realities, which improves decision-making in public policies and community practices (Nkaizirwa *et al*., 2021). In summary, this study underscores the significance of interdisciplinary and innovative methods for achieving sustainable development, encouraging global cooperation and the application of cutting-edge technology to confront challenges at both the international and local levels. The events of 2010 in the south of the Department of Atlántico, Colombia, showed how the waters of the Magdalena River and the Canal del Dique flooded municipalities such as Santa Lucía, Repelón, Candelaria and Manatí due to torrential rains, lack of infrastructure maintenance and government neglect (Llanos Henriquez, 2017). The failure of the Canal del Dique and the inundation of numerous areas stem from a combination of factors, including insufficient state actions and the neglect of maintenance activities in management strategies since 2004. These phenomena caused poverty, economic losses in the agricultural sector, diseases and population displacement, aggravating the proliferation of informal settlements in Barranquilla. As highlighted in the "Third Report of the Citizen Corruption Monitor," the escalation of poverty has resulted in increased social, environmental, and economic risks, largely stemming from the rampant exploitation of ecosystem resources. The Departmental Risk Management Plan for Atlántico points out the absence of policies for mitigating disaster risk and adapting to climate change. The lack of institutional commitment, limited citizen participation and the absence of an integrated platform prevent efficient use of resources. Furthermore, there are currently no metrics available to assess fiscal commitments and initiatives in these domains. A significant challenge lies in the absence of quantitative and bioecological indicators that would aid in tracking threats and risks, particularly within territorial planning plans (TPP). It is essential that this information be accessible to guarantee equity and facilitate decision-making that ensures the sustainability of the territory. Considering the constraints inherent in sustainability research and the data collected, it is essential to develop a territorial bioecological coefficient (TBC), referred to as (CBioET) in Spanish. This coefficient will facilitate the assessment of compliance and advancement concerning the SDGs. To achieve this, it is important to employ suitable tools and methodologies that can effectively identify, measure, or evaluate the sustainability, adaptability, vulnerability, and risks faced by both the territory and its inhabitants, particularly in the context of climate change. This measure aims to provide a comprehensive understanding of how land use practices can align with the natural capacity of ecosystems to sustain life. By integrating various factors, the TBC offers a nuanced perspective that goes beyond traditional sustainability indices. It underscores the importance of considering both biological and physical elements in assessing the sustainability of a region, particularly in relation to human influence (Nketiah *et al.,* 2024). Considering the relevance of the SDG, especially SDG-13, related to climate actions, and the problems associated with climate change, from the economic, social and environmental perspective, this study aimed to develop a TBC model that will serve to quantify progress in development objectives and goals, based on nature, as well as to evaluate environmental components and ecosystem resources in the context of climate change. The study has been carried out in the Department of Atlántico, Colombia, in the period between 2020 and 2023.

MATERIALS AND METHODS

In Colombia and in the municipalities of the Atlántico department, population growth is driving a trend towards spatial expansion of human communities. In the affected areas, the existing natural cover is significantly compromised as a result of urban infrastructure development. Consequently, evaluating this growth with suitable instruments is vital to reduce its impacts. Therefore, in a qualitative

way with some statistical elements (Cohen *et al*., 2018), it is necessary to develop a territorial bioecological indicator that evaluates the level of compliance and progress in the 17 SDGs and their 169 targets, as established by the United Nations. It employs instruments to evaluate sustainability, adaptive capacity, vulnerability, and climate-related risks, taking into account regional characteristics. A TBC is needed to determine compliance through methodologies linked to climate risks. The proposed mathematical model evaluates SDG-13 progress, adapting to territorial conditions to accurately measure development in response to climate change. For a detailed examination of ecological sustainability, the variables identified are crucial as they address significant components of natural ecosystems and human impacts on the landscape. One such variable is 1) *Vegetation cover*, which plays a key role in determining the condition of ecosystems and their potential to provide vital services, such as carbon absorption, water cycle management, and biodiversity protection. 2) *Water cover:* Water is a crucial resource for life and human well-being. This variable evaluates the availability and quality of water bodies, which is vital for the sustainability of any territory. 3) *Linear cover:* It includes areas such as roads, highways, and other linear infrastructures that divide and fragment the surrounding landscape. It is important to analyze their impact on ecological connectivity and energy and nutrient flows. 4) *Urban cover:* Urban growth has a direct effect on territorial sustainability, as it alters natural patterns of land use, increases demand for resources, and generates greenhouse gas emissions. Evaluating this variable is essential for the sustainable management of urban development. Each of these coverages serves as a crucial component for evaluating the relationship between natural environments and human activities, enabling a comprehensive assessment of the territory's bioecological condition. The document outlines sampling techniques for validating the mathematical model of the TBC, primarily focusing on the analysis of satellite imagery and the segmentation of the territory into quadrants. The techniques used are as 1) *Satellite photographs and cartography:* High-resolution satellite images obtained through tools from the Colombian Institute Agustín Codazzi (IGAC) were used to observe and analyze vegetation, water, urban and linear coverage. These images provided a quantitative basis for measuring environmental impact in different years. 2) *Division into quadrants:* The area was segmented into quadrants, each measuring 10 m² per pixel, allowing for an accurate assessment of the coverages being analyzed. Each quadrant was subdivided into four parts to obtain a detailed percentage analysis of the different coverages (1/4 = 0.25%, 2/4 = 0.50%, 3/4 = 0.75%, 4/4 = 1.00%). 3) *Vester methodology:* A matrix was employed in this methodology to rank essential problems, classifying them according to their level of causality, which included weak, medium, strong, and very strong categories. This allowed key environmental problems in the territory to be identified and assigned a relative weight in the analysis. 4) *Percentage analysis:* An approach based on predictive percentages was implemented to assess the level of coverage for each area in the distinct quadrants. This method facilitated the identification of changes in land cover, comparing data from different periods to measure sustainability and the impact of urban growth. By employing these techniques, the mathematical model was validated through the provision of accurate and trustworthy quantitative data, which is vital for calculating the TBC. The validation of the mathematical model for the TBC was carried out using a structured approach in several stages. First, a direct observation of the territory was carried out, using diagnostic tools to identify the ecological and social variables. Following that, a mathematical equation was formulated to encompass critical variables such as vegetation, water, linear elements, and urban land use. The model combined quantitative and qualitative approaches, weighting the variables according to their importance in the territory. The model was validated by temporally comparing data from different years, using satellite images and percentage analysis, applying it to three municipalities in the Atlantic (Usiacurí, Puerto Colombia and Suan). The numerical findings indicated variations in environmental impact and forecasted the future sustainability of the region.

Data collection

This article is dedicated to a holistic cycle in the municipalities of Usiacurí, Puerto Colombia and Suan, geographical areas that host natural ecosystems in the Department of Atlántico (Fig. 1).

The study units and data collection techniques are carried out and presented in a descriptive, comparative,

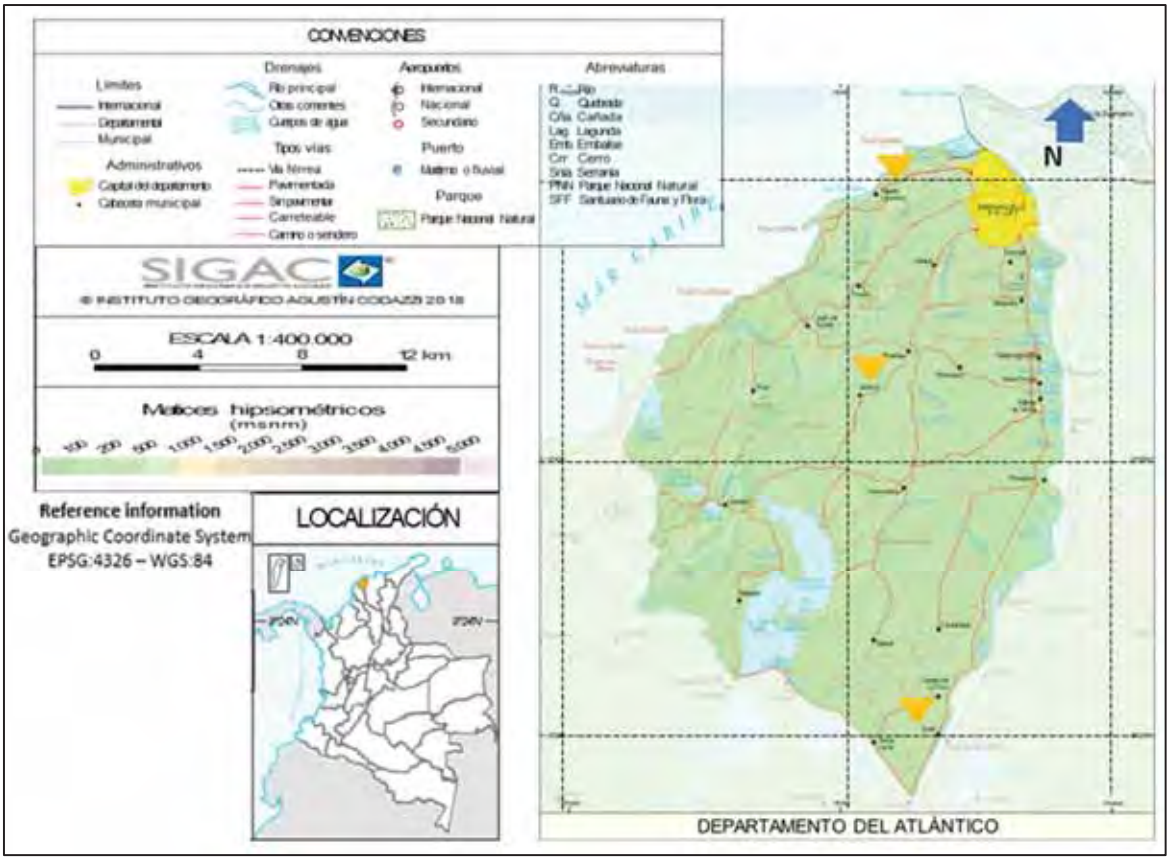
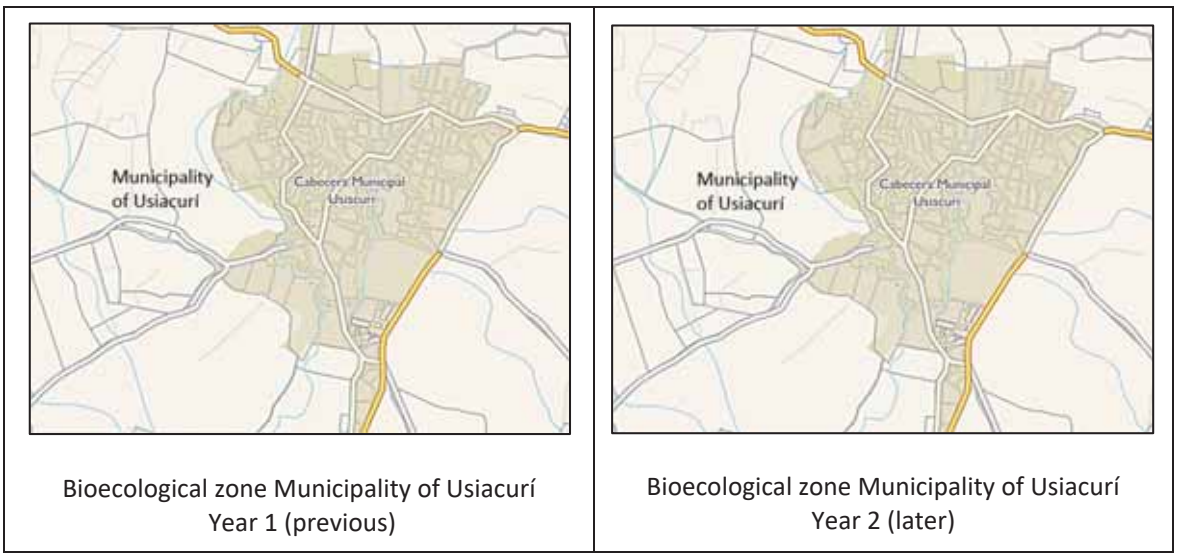


Fig. 1: Geographical location of the study area in the Department of Atlántico, areas of the Municipality of Usiacurí, Puerto Colombia and Suan, using geographic information system (GIS) (IGAC, 2024)

analytical and explanatory manner. Furthermore, it aims to establish a clear framework for the research processes linked to each phase of the analysis, making it applicable to any field or region that is to be studied at local, regional or global level. This approach, which is based on the multifactorial-systematic theory, anticipates the explanatory process of the holistic spiral. In this context, the researcher goes beyond mere speculation regarding the reasons behind events, actively working to synthesize information and experiences in order to generate knowledge that is both significant and applicable. It should be noted that grounded theory uses only qualitative analysis techniques (Hurtado, 2000).

Data analysis

In the analysis of the results, the premise put forward by Amartya Sen is considered, which highlights the external characteristics inherent to the environmental components in the context of sustainable human development. This process is carried out without factoring in human influence, which shapes regions and territories in relation to their economic, social, environmental and climatic systems. Conversely, Maslow posits that internal conditions are unique to specific communities and individuals, making them essential for driving behavioral change within a given territory. These conditions are closely tied to the survival needs and behaviors of the population, influencing sustainability in each region under examination (Maslow, 1943). This implies that the desire to change or modify behaviors to improve environmental conditions depends on people, who must adapt to climate change by implementing plans, programs and projects necessary to carry out actions that improve the quality of life.



Bioecological zone Municipality of Usiacurí Year 1 (previous)

Bioecological zone Municipality of Usiacurí Year 2 (later)

Fig. 2: Photograph taken from the GIS of the Usiacurí Municipality area (IGAC, 2024)

Table 1: Percentage analysis of temporality in the different coverages (Hroub *et al.*, 2025; IGAC, 2024; UN, 2015)

Initial value (year 1)	Temporary value (year 2)
$C.V_1$ = Plant Coverage	$C.V_2$ = Plant Coverage
$C.L_1$ = Linear Coverage	$C.L_2$ = Linear Coverage
$C.H_1$ = Water Coverage	$C.H_2$ = Water Coverage
$C.U_1$ = Urban Coverage	$C.U_2$ = Urban Coverage
$C.V_1 + C.H_1 + C.L_1 + C.U_1 = V1$	$C.V_2 + C.H_2 + C.L_2 + C.U_2 = V2$
$V1 - V2 = Y\%$	

RESULTS AND DISCUSSION

Mathematical model of the territorial bioecological coefficient (TBC)

The development of TBC is based on a qualitative approach (Hurtado, 2000), which allows to numerically explain a quantitative condition for government decision-making. This coefficient aids in recognizing ongoing events and forecasting potential future occurrences by utilizing an index that measures the level of advancement in bioecological elements. It is tailored to align with the environmental attributes of the region as well as the plans, programs, and projects aimed at the area's development. The methodological design was developed using the adapted model proposed by Schavino and Villegas (2010), which encompasses the following stages:

Stage 1: Recognize the variables related to temporality and ecological sustainability through vegetation, water, linear areas, deserts and urban coverage, using cartography and satellite photographs of the study area (Fig. 2), as used by Pérez-Aristizabal *et al*. (2025).

Consequently, the fundamental numerical computations will be executed to determine the primary indicator required for assessing the sustainability of various coverages. This assessment will rely on the presence or absence of the different environmental factors evaluated through the implementation of telemetric plans and the count of observed quadrants, as illustrated in Table 1.

Referring to Table 1, Y percent (%) = (V1-V2) the first identified index of bioecological sustainability that, through the suggested methodology, must be expressed in percentage terms to facilitate the interaction with the other indicators and variables of the analysis method , the bioecological coefficient is identified. At this point in the process, an analysis takes place to establish an indicator that illustrates population growth as outlined in the following:

A review of the TPP for the selected municipality

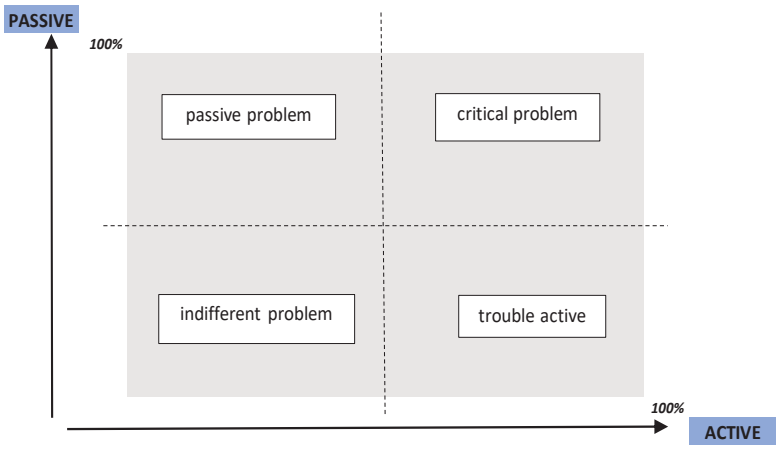


Fig. 3: Analysis of identified problems (Suberi, 2022)

Table 2: Vester methodology value scale (Suberi, 2022)

Scale of value	Description
0	Not causal
1	Weak causal
2	Causal media
3	Strong causal
4	Very strong cause

is undertaken to evaluate the progress made in its development and to determine the extent of its ecological sustainability. This analysis is carried out based on the projection of the population growth of the area, considering the population of the initial period and the current population within the framework of the study. Therefore, the population at the end of period "n" is expressed using Eq. 1 (Betzholtz *et al*., 2025).

Growth "n" = population index (Year 1) – population index (Year 2) (1)

Following the acquisition of the necessary factors and variables, the percentage analysis of the impacts of climate change is initiated. Problems are identified and sorted into categories of critical, indifferent, passive, and active using the Vester matrix. Critical problems for each environmental element are selected to formulate indicators and propose solutions (Fig. 3).

In order to determine how to prioritize projects and programs, as well as to develop an action and improvement plan, this system is evaluated according to the in accordance with the assessment outlined in Table. 2.

An environmental identification registry (EIR) is created to align with the ecological and environmental sustainability aspects of the territory. This process includes an exhaustive analysis of the diagnoses of water, soil, culture, air, social aspects and biodiversity. A percentage-based assessment of the needs will be performed, utilizing the environmental quality index (EQI) specific to the study area. This process will enable the development of a table that details territorial needs, following the principles of the Maslow triangle (Maslow, 1943). The results will be presented in a calculation table (Table 3), which will allow obtaining the percentage assessment necessary for representation in a spider diagram, where the various components of ecological sustainability will be compared.

Stage 2: Implement the variables derived from the percentage analysis of each SDG objective, as follows:

• 17 SDGs are equivalent to 100%, which means that each SDG has a percentage weight of 5.88%.

• The SDGs comprise a total of 169 goals. A percentage analysis is carried out for each of these

Table 3. Percentage analysis by element (Suberi, 2022)

Percentage average environmental diagnosis					
A	Water diagnosis				11.11%
B	Air diagnosis				11.11%
C	Soil diagnosis				11.11%
D	Flora diagnosis	11.11%	Biodiversity Diagnosis		22.22%
	Fauna diagnosis	11.11%			
E	Diagnosis education	11.11%			
F	Housing diagnosis	11.11%	Socioeconomic Diagnosis		44.44%
G	Health diagnosis	11.11%			
H	Employment diagnosis	11.11%			
	Total			0	– 100%

Table 4: Correlation of relative weight of goals and SDG13 (Hroub et al., 2025; UN, 2015)

	GOAL	Relative weight by territorial importance
SDG-13 Climate actions	13.1 Increase resilience and adaptation capacity to climate risks and natural disasters in all territories at local, regional and global levels.	0.71
	13.2 Integrate climate change-related actions into local, national and global policies, strategies and plans	0.71
	13.3 Education, awareness-raising and human and institutional capacities should be promoted to improve climate change mitigation, adaptation to its effects, minimization of its impacts and the implementation of early warnings.	0.71
	13.a Developed countries party to the United Nations Framework Convention on Climate Change must honour their commitment to mobilize a total of US$ 100 billion annually from a variety of sources by 2020. This financing is crucial to address the needs of developing countries in terms of taking concrete mitigation measures and ensuring transparency in their implementation. It is also essential that the Green Climate Fund be put into operation and that it be capitalized as soon as possible.	0.41
	13.b Promote the creation of mechanisms to improve planning and management capacity in relation to climate change in the least developed countries and small island developing States, paying special attention to women, youth and local and marginalized communities.	0.41
	RELATIVE WEIGHT OF SDG 13 GOALS	2.95

goals, resulting in a rating scale of 0.59%. This percentage will be compared with the goals set in SDG 13, multiplying 0.59 by 5, given that this SDG has five goals. Thus, the relative weight of the SDG 13 Goals translates into 2.95%.

• The homologation analysis is carried out in accordance with the existing environmental elements.

• The existing environmental elements in the territory are considered.

• An index of importance of basic ecological needs (water, air, soil, flora, fauna, education, housing, health and employment) is prepared.

• It is formulated from a percentage analysis using qualitative and quantitative techniques by bioecological component, identifying the existing problems in the analyzed territory.

• An index of importance of basic needs is also prepared, which considers both qualitative and quantitative factors.

Stage 3: In this phase, the climatic variations within the studied region will be defined using the Territorial Planning Plans (PPT) alongside telemetry data from

the chosen municipal areas. An initial baseline will also be established to characterize the bioecological components under investigation. The previous PPTs will be chosen and through their historical analysis in the different plans, programs and projects, the ecological resilience of the area in question can be evaluated. Based on the gathered indicators, an analysis is conducted utilizing a homologation table to assess the advancement of the 17 municipal SDGs. This evaluation informs decisions regarding the direction of the PPT for upcoming terms, allowing for necessary reorganizations or enhancements (Table 5).

The construction of the TBC was determined through Eq. 2 (IGAC, 2024), where the sum of the telemetric variables, population growth and the sum of indicators of the Vester matrix, the environmental identification registry and the relative weight of the goals of the SDG, gives us the first percentage analysis of compliance with SDG-13, using Eq. 2 (Hroub *et al*., 2025; IGAC, 2024; UN, 2015):

$$TBC = \frac{[V1 - V2]\% + IVe\% + EIR\% + Crp\% + PODS\%}{5} \quad (2)$$

Where:

V1 -V2: Photographic or cartographic method (telemetry)

IVe: Vester homologation indicator

EIR: Environmental identification registry

CrP: Population growth

PODS: Percentage of the relative weight of each SDG

In order to analyze the application of the mathematical formula within the municipality of Usiacurí, a comprehensive summation of the indices for each analyzed element is performed. Based on this information, the corresponding indicator is substituted to calculate the TBC, using Eq. 3 (IGAC, 2024; Suberi, 2022):

Telemetric temporality difference:

$$V1 - V2 = Y\% = 0.103\% \quad (3)$$

To obtain the Vester percentage index, proceed as Table 6.

For the final consolidation by IRE Municipality of Usiacurí, the following result is established for each environmental element analyzed.

The results are obtained using Eq., 4 (IGAC, 2024; Suberi, 2022):

$$IER(\text{average}) = 1.75 + 0.44 + 2.24 + 1.66 +$$

Table 5: Percentage analysis of SDG progress (Hroub *et al*., 2025; UN, 2015)

Studied area	TBC (%)	Analyzed (%)	Progress in territorial SDG management
Department Area of the Atlantic	To find the percentage value	SDG relative weight of the 169 SDG targets of 100% of the total	Percentage analysis required, actions to be developed to improve the sustainability of the area studied.

Table 6 : Consolidation of clothing indices for each element (Suberi, 2022)

Vester index by environmental element		Percentage analysis of vesting by element	
IVe (Flora)			6.66
IVe (Fauna)			6.25
IVe (Water)			6.25
IVe (Air)			6.66
IVE (Floor)			6.66
IVe (Education)	6.66	IVe (Socioeconomic)	$\frac{6.66 + 6.25 + 5.00 + 6.66}{4} = 6.14\%$
IVe (Housing)	6.25		
IVe (Health)	5.00		
IVe (Employment)	6.66		
Total, IVe average			6.438%

Table 7: Environmental Identification Registry (IGAC, 2024; Suberi, 2022)

Environmental elements	Relative percentage weight identified
IER (Flora)	1.75
IER (Fauna)	0.44
IER (Water)	2.24
IER (Floor)	1.66
IER (Air)	2.41
IER (Socioeconomic)	1.89
IER (average)	1.73

Table 8: The percentage values of compliance with TBC for each municipality analyzed (Hroub et al., 2025; IGAC, 2024; UN, 2015)

TBC of the Municipality of Usiacurí	TBC of the Municipality of Puerto Colombia	TBC of the Municipality of Suan
14.403%	13.77%	15.5%

Table 9: The percentage factor of non-compliance with SDG-13 would be the difference of 100% (Hroub *et al*., 2025; UN, 2015)

TBC of the Municipality of Usiacurí	TBC of the Municipality of Puerto Colombia	TBC of the Municipality of Suan
(85.60%)	(86.23%)	(84.50%)

$$2.41+1.89=\frac{10.39}{6}=1.73 \quad (4)$$

Population difference in the temporality studied as $CrP=0.26\ \%$

The percentage weight of the 17 SDGs is 5.88%, giving an equal percentage to each SDG analyzed as $\mathrm{PODS}=5.88\%$.

By replacing the results obtained, using Eq., 5 (IGAC, 2024; Suberi, 2022):

$$\text{Total TBC}=0.103\%+6.43\%+0.26\%+1.73\%+5.88\%=14.403\% \quad (5)$$

The result obtained is divided by the number of variables found, which in the case of TBC is 5, depending on the number of items analyzed, using Eq., 6 (IGAC, 2024; Suberi, 2022):

$$\text{TBC}\left(\text{Municipality of Usiacurí}\right)=\frac{14.403}{5}=2.880 \quad (6)$$

The utilization of the equations and the examination of the variables pertinent to TBC yields results that offer valuable insights into directing the administrative management systems and municipal governance across the various territories studied. This analysis helps to clarify the necessary plans, programs, and projects that should be prioritized for implementation at the municipal level (Table 8).

According to the information presented in Table 9, it has been found that the analyzed territories do not meet all the goals defined by SDG-13. The percentage analysis indicates 85.60% for Usiacurí, 86.23% for Puerto Colombia and 84.50% for the Municipality of Suan (Table 9).

The considerable difference observed between the territories analyzed and the fulfilment of the SDG - 13, which focuses on “Climate Action”, raises a crucial debate on the challenges faced by the local community in its fight against climate change. The non-compliance with the evaluated indicators in the relevant areas highlights a notable divide between international targets and the current realities experienced locally. This discrepancy highlights the urgent need to adopt concrete and effective measures to address territorial ecological damage at local, national and global levels. It is essential to analyze and identify the causes of non-compliance with the SDGs, in particular SDG 13, in the territories under study. If suitable measures are not executed in a timely fashion, this non-compliance could lead to a significant environmental crisis. Moreover, the elements leading to this non-compliance could involve insufficient technical, human, and financial resources, ineffective policy frameworks, and a low

level of environmental consciousness. Recognizing these causes is essential to formulate effective strategies that meet the particular needs of each territory. In short, the active participation of the local community and environmental education are key aspects to improve compliance with SDG 13 in the territory analyzed. Involving citizens in climate change mitigation and adaptation actions can be decisive in facing climate challenges and promoting SD in the area. Emphasizing the necessity of enhancing cooperation among local governments, non-governmental organizations, the private sector, and civil society is crucial (UN, 2015). Cooperation between different sectors is essential for the formulation and implementation of comprehensive policies and climate action programs that address the underlying causes of non-compliance and promote SD in the Department of Atlántico. This scenario not only represents a challenge but also provides an opportunity to strengthen the resilience of communities and foster SD in the region. Failure to comply with SDG 13 (climate action) poses a critical challenge for the territories under study, as it could aggravate the climate crisis if timely measures are not taken. As stated by the UN (2015), it is vital to engage in multi-sector collaboration to effectively confront the fundamental causes of this challenge, which include resource scarcity, inadequate policies, and and a lack of environmental consciousness. Comparatively, authors such as Gupta and Vegelin (2016) have highlighted that the integration of inclusive and participatory policies can be decisive in moving towards sustainable development, which coincides with the need to involve local communities in climate mitigation, restoration and adaptation. In addition to emphasizing the significance of ecosystem services in advancing the SDGs, the enhancement of environmental education, as discussed in the text, aligns with their findings by fostering transformative changes in local practices. Finally, strategies must be adapted to the particularities of each territory, an idea that reinforces the need for a territorial approach, such as that proposed by Behera *et al.* (2024) in their analysis of the links between renewable energy and SD in emerging economies. This plays a significant role in promoting and realizing the SDGs fairly, while acknowledging different territorial contexts, and aids in decision-making through the application of a TBC mathematical formula relevant to multiple scientific disciplines. It is essential to redefine the ecological security index and the concept of territorial ecological sustainability, taking into account the environmental, ecological and social particularities of each municipality and the areas where the SDGs are sought to be implemented through a territorial bioecological index. This study suggests that the concept of "territorial bioecological coefficient (TBC)" refers to the extent of utilization, alteration, diminishment, rehabilitation, and sustainable management of natural resources. It emphasizes the importance of preserving current ecological standards while ensuring that the foundational natural environment remains secure. for future generations. This concept, according to the author of this study, is based on Maslow's human conditions. Considering hierarchical structures in relation to human, biological, and physiological needs necessitates an understanding of the livelihoods of the communities and inhabitants in the region where the formula is utilized. To address these premises, it is crucial to establish a TBC that evaluates the degree of compliance with social, economic, political, technical, financial and cultural conditions, in order to monitor progress towards the SDGs. The use of simple, clear and precise methodologies is proposed, which reflect the regional reality and the achievement of the 169 goals of the SDGs. The goal is to integrate natural sciences, including physics, chemistry, and biology, with social sciences to enhance the visualization of advancements in territorial plans, programs, and projects through a mathematical model. This will allow governments to make appropriate decisions related to climate change mitigation and adaptation, incorporating these strategies into environmental risk management systems, regardless of administrative changes during government periods. Utilizing a mathematical framework will support the analysis of how the administrative policies of different mayors can be organized to acquire the necessary resources aimed at improving the living standards of their residents. The term "territorial bioecology" arises from the identification of territorial variables evident from the sustainability of the area studied, integrating the components that are part of this mathematical model on climate change. A comprehensive strategy was crafted for three separate areas, confirming the results within diverse environmental settings and evaluating their specific geographical and geospatial

conditions in maritime, river, and savanna landscapes. In these territories, indicators and coefficients can be validated without taking into account periods of governance, analyzing the population's capacity to adapt to climate change and the potential risks of not carrying out actions that improve living conditions. The development and evaluation of the TBC, established in this research, enables an exhaustive and critical analysis of its relevance, applicability and potential impact on progress towards the SDGs. This instrument provides a credible means to tackle the distinct issues of environmental sustainability in at-risk areas such as the Department of Atlántico in Colombia, where the consequences of climate change are particularly severe. However, success in its implementation is conditional on the ability to overcome the environmental, social, economic and political limitations inherent to the local and national context. The TBC is characterized as a novel methodological approach that integrates biotic, abiotic, and socioeconomic factors within a specific analytical structure to evaluate the sustainability of territories. As highlighted by recent studies in environmental management of environmental sustainability (Unceta, 2014) and territorial analysis methodologies (Wang and Bao, 2021), this integration allows identifying discrepancies and opportunities in economic, environmental and social management, contributing to the strengthening of adaptation capacity of territories to climate threats. Furthermore, TBC enhances the relationship between scientific understanding and policy creation, ensuring a seamless integration of local factors with the global commitments outlined in the 2030 Agenda. It is crucial to consider the criticisms raised regarding the generalized applicability of the SDGs, which often do not reflect the particularities of the most vulnerable regions. Insufficient contextual adaptation and the lack of concrete tools for sector-specific implementation have contributed to a disparity in goal attainment. Specifically, in the Atlantic area, the deficiencies in both technical capabilities and human resources within municipalities reveal the importance of adopting approaches such as TBC, which enable a more localized and relevant analysis. A notable aspect is the identification of structural barriers that hinder sustainable development. These include lack of financial resources, institutional weakness and administrative fragmentation, especially in small and medium-sized municipalities. Moreover, the restricted awareness among authorities and communities concerning the extent of climate impacts complicates the process of making effective and timely decisions. In this context, TBC not only faces technical challenges inherent to its application, such as obtaining reliable data and building local capacities, but also the need to generate political will to integrate this type of tools in territorial planning. The findings indicate that the implementation of the SDGs is impeded by political and cultural differences, as well as the Congreso of the Republic of Colombia's insufficient interest. This underlines the need for a legislative framework that prioritizes climate action and ensures adequate resources. Moreover, the application of satellite telemetry alongside accessible technological resources in territorial evaluation is identified as a crucial strength of TBC, allowing for precise evaluations of ecological and social circumstances. These data, historical and current, allow for more effective territorial planning based on evidence. The development of mathematical models that incorporate bioecological and socioeconomic variables is also highlighted as a key tool to evaluate and monitor progress towards the SDGs. Creating these models demands an interdisciplinary approach that combines insights from the natural, social and technological sciences. In addition, ensuring that these models are both interpretable and functional for local decision-makers is of utmost importance. The use of tools such as satellite images and the aforementioned percentage analyzes reinforce the viability of TBC to generate territorial diagnoses that combine objective quantification and qualitative observations. Studies such as those by Wang and Bao (2021) have shown how telemetry can provide valuable data for territorial planning, while Wackernagel and Rees (1996) highlight the importance of visual indicators in sustainability assessment. This enables the assessment of changes in environmental factors such as water, soil, and vegetation, as well as the evaluation of the effects of human activities on these ecosystems. For example, population growth and urbanization stand out as factors that decrease territorial sustainability. The dialogue surrounding the reallocation of the significance of the SDGs, tailored to the specific needs and capacities of different territories, holds considerable relevance. In regions such as the

Atlantic, where climate vulnerability is high, it may be necessary to prioritize objectives such as climate action (SDG-13) or poverty eradication (SDG 1) over others that have a less immediate impact. Nevertheless, this approach brings forth ethical and operational issues. One concern is the possibility of fostering inequalities between regions as a result of uneven resource allocation. On the other hand, the variability in the implementation of the SDGs could hinder the global comparability of progress and the coordination of international efforts. Achieving a balance between local adaptability and global consistency is essential, alongside the promotion of environmental and social equity. The TBC is presented as an innovative methodological tool by integrating biotic, abiotic and socioeconomic components and the elements of water, air, soil, flora, fauna, education, housing, health, employment, within a specific analytical framework to evaluate territorial sustainability. As highlighted by recent studies in environmental management of environmental sustainability (Unceta, 2014) and territorial analysis methodologies (Wang and Bao, 2021), this integration allows identifying discrepancies and opportunities in economic, environmental and social management, contributing to the strengthening of adaptation capacity of territories to climate threats. Moreover, TBC enhances the relationship between scientific understanding and policy creation, ensuring a seamless integration of local factors with the global commitments outlined in the 2030 Agenda. It is important to consider the criticisms raised regarding the generalized applicability of the SDGs, raised by the United Nations and especially SDG-13 (climate action), which often do not reflect the particularities of the most vulnerable regions. The lack of contextual adaptation and specific sectoral and specific scientific tools for its implementation has resulted in uneven fulfillment of the goals. In the case of the Department of Atlántico, the technical, financial, economic and human deficiencies in the municipalities highlight the need for approaches such as TBC, which allow an analysis adjusted to local conditions. A significant factor is the acknowledgment of structural challenges that obstruct sustainable development. These include the dependence of municipalities on the central government, lack of their own financial resources, institutional weakness and administrative fragmentation, especially in small and medium-sized municipalities. The research correctly points out that social, environmental, political and cultural differences, as well as the lack of interest in the Congress of the Republic of Colombia, constitute a significant obstacle to the implementation of the SDGs. This highlights the importance of establishing a legislative framework that prioritizes climate action and ensures the appropriate allocation of resources. Utilizing satellite telemetry alongside accessible technology for territorial analysis stands out as one of the most promising elements of TBC. The ability to make accurate diagnoses of ecological and social conditions, using historical and current data, allows planning to be guided more effectively and based on evidence. The development of these models necessitates a collaborative effort that brings together expertise from natural, social and technological sciences. Furthermore, it is essential to ensure that these models are understandable and usable by local decision makers. This allows not only to measure variations in environmental coverage such as water, soil and vegetation, but also to analyze the impacts of human activities on these systems. For example, population growth and urbanization stand out as factors that decrease territorial sustainability. The redistribution of the relative weight of the SDGs based on territorial needs and capacities is a crucial issue, especially in vulnerable regions such as the Atlantic. Here, climate action (SDG-13) and poverty eradication (SDG-1) may require higher priority due to their immediate impact compared to other goals. However, this strategy faces significant challenges. Unequal distribution of resources may exacerbate regional disparities, and inconsistencies in the execution of the SDGs could impede global comparability and international coordination. The balance between local flexibility and global coherence is essential to guarantee environmental and social justice, promoting inclusive and equitable sustainable development. This study also suggests that certain territories could benefit from the application of specific methodologies such as the Vester matrix, widely recognized for its usefulness to identify causes and effects of environmental problems in a systemic way. By utilizing this tool alongside percentage analyses and satellite monitoring, a more accurate determination of adherence to the SDGs could be achieved. Furthermore, the success of TBC also depends on the ability of local communities to take

ownership of the planning and decision-making process. This study highlights how environmental education fosters awareness and civic engagement, while local participation shapes territorial strategies. Integrating education with environmental needs enhances skills, innovation, and resilience, supporting climate actions and SDGs. Projects that prioritize sustainability, including homes tailored to withstand climate variations, contribute to achieving these aims. The study also explores the ethical dilemma of conserving resources for future generations. This concern has been highlighted in works such as those of, who analyze the principles of sustainability, and Wackernagel and Rees (1996) in their formulation of the ecological footprint as a tool to evaluate resource consumption against the planet's regeneration capacity. This strategy is pivotal to the principle of sustainability, indicating a need to balance immediate demands with the safeguarding of natural assets. To address this dilemma, the development of mathematical mechanisms is proposed that allow calculating the sustainable use of environmental resources, ensuring their availability for future generations. Likewise, the integration of measurement instruments such as the ecological footprint and additional sectoral indicators could augment the TBC, delivering a wider understanding of environmental dynamics and their influence on territorial sustainability. However, its implementation requires overcoming technical barriers and guaranteeing the participation of key actors, from local governments to communities. This TBC model goes beyond current methodologies by taking into account key differences: In terms of the Territorial Approach, while many ecological indices have a global or national focus, the TBC emphasizes a detailed analysis at the territorial or regional level. This facilitates the evaluation of how well a specific region can accommodate certain human activities without jeopardizing its ecological sustainability over the long term. Other indices, such as the Ecological Footprint, tend to generalize the environmental impact more, which can omit local particularities. In the case of Bioecological Integration, the TBC not only measures the impact of human activity in terms of emissions or resource consumption, but also how these activities directly affect biodiversity, nutrient cycles, and site-specific ecological flows. Conversely, a significant number of sustainability indices concentrate predominantly on metrics like greenhouse gas emissions, energy consumption, or resource efficiency, frequently failing to account for the complex interactions within bioecological systems. In relation to the social and cultural components, another differentiating aspect of the TBC is that it can include social and cultural variables that are deeply intertwined with the use of the territory and respect for ecosystems. In areas where indigenous communities reside, the TBC might include the ways in which traditional knowledge supports the sustainability of the land. Conventional ecological indices can overlook these cultural factors and their contribution to sustainability. Regarding the dynamic adjustment to local conditions, the TBC is developed at the territorial level and can dynamically adjust to the changing conditions of that specific ecosystem, taking into account its resilience, the ecosystem services it provides, and the environmental pressures to which it is subjected. Typically, global or national sustainability indices lack flexibility and are based on general metrics that do not consistently represent the unique characteristics of specific geographic area. Compared to similar models, there is no information at the regional and national level. At the international level, the ecological security index models of Wang and Bao (2021) and the Ecological Footprint of Wackernagel and Rees (1996) are used as a reference for comparison. This evaluation enhances the viewpoint on sustainability management and ecological security at multiple scales. Below, we outline significant attributes of the three models (Table 9):

This TBC takes into account different aspects to those reported by (Imelda and Hidayat, 2024; Jiménez-Bedoya et al., 2024; Teweldebrihan and Dinka, 2024) who have been concerned about specific ecosystems such as water, agriculture and territory, since it focuses on four coverages: water, vegetation, urban planning and linear (roads, paths, etc.). In conclusion, the achievement of TBC and similar instruments hinges on a unified strategy that merges scientific understanding, political determination, and community engagement. This combination is essential to meet the challenges of climate change and move towards genuine sustainability, as it becomes a crucial challenge regarding bioecological sustainability as well as the need to overcome structural barriers that hinder sustainable development, the lack of financial resources, administrative fragmentation

Table 10: Comparison of TBC with other existing ecological models

Criterion	Ecological security model (Wang and Bao, 2021)	TBC	Ecological footprint
Approach	Ecological security in large urban agglomerations (Beijing-Tianjin-Hebei). Considers air quality, water resources and soil protection.	Evaluation of land use in municipalities of Colombia, considering ecological coverage (vegetation, water, infrastructure, urban development).	It measures human demand on natural resources at a global level, without a focus on ecological security.
Variables considered	Land use, water bodies, air quality, biodiversity, urban expansion. It also evaluates infrastructure to mitigate environmental disasters and maintain ecological stability.	Territorial coverage (vegetation, water, urban and linear), social and economic factors (education, housing, employment). Considers anthropic and abiotic elements.	Resource consumption and carbon emissions. It does not assess ecological security variables or territorial infrastructure.
Scale and applicability	Large urban regions. Seek balance between economic development and environmental conservation. Consider infrastructure planning for sustainability.	Local and regional territories (municipalities of the Department of Atlántico in Colombia). Provides detailed overview of local environmental impact.	Global application, although it can be used at different scales. Designed to measure the aggregate impact of humanity on the planet.

and poor institutional capacity, especially in small and medium-sized municipalities. The situation is further complicated by the narrow understanding of authorities and communities regarding the impacts of climate change and the urgency of these issues, hindering the effective implementation of tools such as the TBC. Other challenges of this project are the training of local capacities for the correct use of this mathematical model. Additionally, a strong political will is required to embed the TBC within territorial planning at local, regional, and various other areas of the country, aiming for improved implementation of the model.

CONCLUSION

The findings of this study reveal a crucial link between the TBC and the successful realization of the United Nations' SDGs. It is imperative to engage in research that focuses on developing mathematical frameworks capable of evaluating the territorial and bioecological dimensions that play a vital role in fostering SD worldwide.. The department of Atlántico faces significant challenges derived from climate change, including alterations in weather patterns, pressure on natural resources and limitations in the capacity of authorities to implement effective measures. The lack of community empowerment underlines the urgency of adopting an integrated approach that adapts to the territorial reality and strengthens local resilience. For this to be achieved, both the central government and local authorities need to take a proactive stance in managing the environment and adapting to climate change, ensuring that the implementation of the SDGs is grounded in a thorough comprehension of regional attributes. Therefore, with the TBC, a new vision of analysis of bioecological and territorial elements begins, leading to the management of local and national plans, programs and projects. This study proposes a methodology that links environmental management systems with municipal planning, promoting sustainability in some territories of the department of Atlántico. TBC serves as a crucial instrument in harmonizing the use of natural resources with their preservation, thereby safeguarding the welfare of both present and future generations. The use of satellite images, environmental records and population growth analysis allowed a better understanding of the environmental and urban dynamics of each municipality. The relationship between population growth and the reduction of natural resources justifies the implementation of more effective environmental management strategies. Technologies such as satellite telemetry and the EIR support the evaluation of the current state and the recognition of past trends, both of which are critical for planning proactive strategies in response to extreme events. Finally, it is essential to develop strategies that optimize decision-making from the central government, together with local initiatives that encourage community participation. The implementation of a comprehensive plan based on the Deming quality cycle will guarantee the success of environmental management programs.

Moreover, prioritizing the expansion and validation of tools such as the TBC in different areas is crucial for reinforcing the effective realization of the SDGs. This study represents a first step towards optimizing environmental management in the context of climate change, providing territories with concrete and effective tools for the execution of regional plans, programs and projects that promote sustainable, equitable and resilient development. To enhance environmental management and SD in the Atlántico department, it is advisable to create a municipal environmental observatory that leverages satellite imagery and environmental data to assess the effects of climate change. In addition, a territorial environmental management system is proposed that links municipal planning with conservation strategies. It is key to encourage citizen participation through environmental education and incentives for sustainable local initiatives. The implementation of circular economy models and climate resilience plans will ensure efficient management of natural resources. It is recommended at the political level to revise the regulatory framework, decentralize the management of environmental issues, and encourage investment in scientific research and technological advancements. It is also essential to integrate sustainability into economic planning, create a climate change adaptation fund and establish indicators to evaluate the progress of the SDGs in each municipality.

SUGGESTIONS FOR FUTURE AREAS OF RESEARCH

The development and validation of the TBC is based on advanced mathematical models that allow its effectiveness to be evaluated in various regional contexts. These models integrate environmental, social and economic variables to offer a complete view of its impact and sustainability. By engaging in comparative studies, the goal is to authenticate and modify the TBC, ensuring it is suitable for diverse environments. In addition, environmental management and adaptation to climate change in the Department of Atlántico are investigated, analyzing local policies aligned with the 17 SDGs. The objective is to improve community practices to face climate and natural resource management challenges. This encompasses the assessment of institutional capacity, the implementation of resilience strategies, and the creation of a regional approach that is customized to the unique features of the Department of Atlántico. In conclusion, these proposals are designed to bridge the recognized gaps, laying a strong groundwork for future research and increasing the effectiveness of environmental policies and global sustainability initiatives. 1) Integrating science and technology into municipal planning through telemetry and satellite data, applying the use of remote sensing and telemetry technologies for the collection of environmental and urban data and evaluating the data that can be used for more effective planning and management of SD. 2) Analyzing historical patterns and research derived from satellite imagery and environmental data to forecast potential challenges and enhance preventive strategies, serving as a guiding framework for current leaders in governance. 3) Improving local strategies and analysing SDG compliance, using methodologies that prioritise the SDGs at the territorial level. It is essential to investigate the allocation of relative weights to the SDGs necessary to progress on local goals, so that the particular priorities and needs of each municipality are reflected. This could involve the development of assessment tools that are adapted to various local, national and global contexts. 4) The creation of assessment tools aimed at validating and broadening the application of instruments like TBC in various regions to evaluate their relevance and efficacy in diverse settings. 5) Promoting community engagement and participation in studies on urban initiatives, in order to investigate how to foster engagement in environmental management and the implementation of the SDGs, evaluating local strategies that have proven effective in involving the population in decision-making and in the implementation of environmental policies. 6) Educational programs and training initiatives aimed at community leaders and local officials focused on natural resource management and climate change adaptation. 7) Case studies from different regions to identify successful practices and lessons learned in the implementation of climate change adaptation and mitigation strategies through TBC. 8) This analysis focuses on the assessment of the Deming Quality Cycle as a framework for integrating quality systems within public administration. It aligns with the execution of the SDGs and emphasizes its application in environmental management. The evaluation aims to highlight how this approach can enhance the effectiveness of both administrative and financial

processes in the delivery of SD initiatives

AUTHOR CONTRIBUTIONS

R. Zapata-Stacey performed the conceptualization, methodology, supervision, writing of the original draft; D. Pinto Osorio assisted to analyse the data and validation; C.A. Rodríguez-Nieto performed the editing, drafting the original draft and review; M. Machado Penso reviewed, visualization and supervised the whole writing.

ACKNOWLEDGEMENT

This study was carried out within the framework of the Doctorate in Sustainable Development as a requirement to obtain the Ph.D. degree. The data analysis and the preparation of the research article were part of the project entitled "Territorial bioecological coefficient as a measure of climate adaptation according to sustainable development: Case study: Department of Atlántico–Colombia". The correction of the manuscript has the support of the research project of the Universidad de la Costa y el Servicio Nacional de Aprendizaje. This study is part of the projects: Teaching project coded by [DOC.100-11-001-18] Universidad de la Costa and Servicio Nacional de Aprendizaje – SENA.

CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
TBC	Territorial Bioecological Coefficient
C.V1	Plant coverage
C.L1	Linear coverage
C.H1	Water coverage
C.U1	Urban coverage
CrP	Population growth
COP26	Conference on climate change
EIR	Environmental identification registry
EQI	Environmental quality index
GIS	Geographic information system
IGAC	Instituto geográfico Agustin Codazz
IVe	Vester homologation indicator
PODS	Percentage of the relative weight of each SDG
SD	Sustainable development
SDG	Sustainable development goal
SDGs	Sustainable development goals
SDG13	Sustainable Development Goals 13-climate action
STEM	Science, technology, engineering and mathematics
TPP	Territorial planning plans
V1	Initial value

V2	Temporary value
V1 -V2	Photographic or cartographic method

REFERENCES

Álvarez Ariza, J.; Olatunde-Aiyedun, T. G., (2024). A systematic literature review on STEAM pre- and in-service teacher education for sustainability: Are teachers ready? Eurasia J. Math. Sci. Technol. Edu., 2498: 1-17 **(17 pages).**

Behera, B.; Behera, P.; Sethi, N., (2024). Decoupling the role of renewable energy, green finance and political stability in achieving the sustainable development goal 13: Empirical insight from emerging economies. Sustainable Dev., 32(1): 119-137 **(18 pages).**

Betzholtz, P. E., Forsman, A.; Franzén, M., (2025). The impacts of climate and the extreme drought in 2018 on population growth in Swedish moth species. Insect Conserv. Divers., 1-9 **(9 pages).**

Chan, S.; Boran, I.; Van Asselt, H.; Ellinger, P.; Garcia, M.; Hale, T.; Shrivastava, M.K., (2021). Climate ambition and sustainable development for a new decade: A catalytic framework. Global Policy. 12(3): 245-259 **(14 pages).**

Cohen, L.; Manion, L.; Morrison, K., (2018). Research methods in education. Routledge **(916 pages).**

Dernbach, J.C.; Cheever, F., (2015). Sustainable development and its discontents. Transnatl. Environ. Law. 4(2): 247-287 **(40 pages).**

Eilks, I., (2015). Science education and education for sustainable development –Justifications, models, practices and perspectives. Eurasia J. Math. Sci. Technol. Edu., 11(1): 149-158 **(10 pages).**

Fábregas Villegas, J.; Tovar Ospino, I.; Palencia Díaz, A., (2024). Electrification as a development and sustainability approach in rural areas using renewable energy sources. Global J. Environ. Sci. Manage., 10(4): 2115-2126 **(11 pages).**

IGAC, (2024). Instituto Geográfico Agustín Codazzi. IGAC-Colombia **(5 pages).**

Imelda; Hidayat, R., (2024). Climate change impacts, adaptation and mitigation in the agricultural sector. Global J. Environ. Sci. Manage., 10(3): 1457-1476 **(19 pages).**

Gómez, C., (2018). Objetivos de Desarrollo Sostenible (ODS): una revisión crítica. Papeles de relaciones Ecosociales y Cambio Global. 140: 107-118 **(12 pages).**

Gökel, Ö.; Dağlı, G., (2017). Effects of Social Skill Training Program on Social Skills of Young People. Eurasia J. Math. Sci. Technol. Edu., 13(11): 7365-7373 **(9 pages).**

Gündüz, Ş., (2017). A research about attitudes and behaviors of university students with having different cultures towards the environment through sustainable development. Eurasia J. Math. Sci. Technol. Edu., 13(6): 1881-1892 **(12 pages).**

Gupta, J.; Vegelin, C., (2016). Sustainable development goals and inclusive development. Int. Environ. Agreements: Politics Law Econ., 16(3): 433-448 **(16 pages).**

Hroub, H.; Rahbeh, M.; Zoubi, M.M.; Abu-Afifeh, Q.Y.; Al-Jawaldeh, H.; Obeidat, N., (2025). Projection of future temperature variations in river basins under climate change scenarios using general circulation models. Global J. Environ. Sci. Manage., 11(2): 1-24 **(24 pages).**

Hurtado de Barrera, J., (2000). Metodología de la Investigación Holística. Caracas: Fundación Sypal. **(1.324 pages).**

Husamah, H.; Suwono, H.; Nur, H.; Dharmawan, A. (2022). Sustainable Development Research in Eurasia Journal of Mathematics, Science and Technology Education: A Systematic Literature Review. Eurasia J. Math. Sci. Technol. Edu., 18(5): 1-19 **(19 pages).**

Jauhari, S.; Minarsih, S.; Hindarwati, Y.; Pramono, J.; Susila, A.; Sudarto, S.; Samijan, S., (2025). Rice yield enhancement and environmental sustainability with precision nutrient management. Global J. Environ. Sci. Manage., 11(1): 77-92 **(16 pages).**

Jiménez-Bedoya, A.; Fuentes-Gandara, F.; Paternina-Uribe, R.; Pinedo-Hernández, J., (2024). Perception and adaptation to climate change in vulnerable regions. Global J. Environ. Sci. Manage., 10(4): 1-18 **(18 pages).**

Li, T.; Liu, Y.; Ouyang, X.; Zhou, Y.; Bi, M.; Wei, G., (2024). Sustainable development of urban agglomerations around lakes in China: Achieving SDGs by regulating ecosystem service supply and demand through new-type urbanization. Habitat Int., 153: 103206 **(17 pages).**

Liu, T.; Wang, H. Z.; Wang, H. Z.; Xu, H., (2021). The spatiotemporal evolution of ecological security in China based on the ecological footprint model with localization of parameters. Ecol. Ind., 115-130 **(16 pages).**

Liu, Y.; Lü, Y.; Fu, B.; Zhang, X., (2023). Landscape pattern and ecosystem services are critical for protected areas' contributions to sustainable development goals at regional scale. Sci. Total Environ., 881: 163535 **(11 pages).**

Llanos Henríquez, E., (2017). Problemática espacial del sur del departamento del Atlántico y la planeación territorial estratégica. Edu. y Hum., 19(32): 159–173 **(15 pages).**

Maashi, K. M.; Kewalramani, S.; Alabdulkareem, S. A., (2022). Sustainable professional development for STEM teachers in Saudi Arabia. Eurasia J. Math. Sci. Technol. Edu., 18(12): 1-14 **(14 pages).**

Maslow, A.H., (1943). A theory of human motivation. Psychol. Rev., 50(40): 370–396 **(26 pages).**

Mensah, J., (2019). Sustainable Development: Meaning, History, Principles, Pillars, and Implications for Human Action: Literature Review. Cogent Soc. Sci. 1(5): 1–21 **(21 pages).**

Morote, A.-F.; Olcina, J., (2023). Cambio climático y

educación. Una revisión de la documentación oficial. Documents d'Anàlisi Geogràfica. 69(1): 107-134 **(28 pages).**

Nkaizirwa, J.P.; Nsanganwimana, F.; Aurah, C.M., (2021). Reexamining the Measurement of Pro-Environmental Attitudes and Behaviors to Promote Sustainable Development: A Systematic Review. Eurasia J. Math. Sci. Technol. Edu., 17(9): 1-21 **(21 pages).**

Nketiah, E.; Song, H.; Adjei, M.; Obuobi, B.; Adu-Gyamfi, G., (2024). Assessing the influence of research and development, environmental policies, and green technology on ecological footprint for achieving environmental sustainability. Renew. Sustain. Energy Rev. 199: 1-12 **(12 pages).**

Onoshakpokaiye, O.E., (2023). An overview of reasoning ability in mathematics and mathematics achievement of students in tertiary institution. Int. J. Indones. Edu. Teach., 7(2): 309-318 **(10 pages).**

Pérez-Aristizábal, J. D.; Puerta-Avilés, O.; Jiménez-Caldera, J.; Caballero-Calvo, A., (2025). Landscape Transformations (1987–2022): Analyzing Spatial Changes Driven by Mining Activities in Ayapel, Colombia. Land, 14(1): 1-24 **(24 pages).**

Rocasolano, M.M., (2019). Derecho, manipulación climática mediante técnicas de Geoingeniería y objetivo 13 del desarrollo sostenible, la acción por el clima. La voz Que clama en el desierto. Revista Opinião Jurídica. 17(26): 166-193 **(27 pages).**

Schavino, N.; Villegas, C. (2010). De la teoría a la praxis en el enfoque integrador transcomplejo. Congreso Iberoamericano de Educación Metas. Buenos Aires **(12 pages).**

Suberi H.K., (2022). Research Analysis of Built Environment as a System: Implementing Research Through Design Methodology. Front. Built Environ., 7: 1-17. **(17 pages).**

Teweldebrihan, M. D.; Dinka, M. O., (2024). The impact of climate change on the development of water resources. Global J. Environ. Sci. Manage., 10(3): 1359-1370 **(12 pages).**

Tu, J.C.; Chen, Y.Y.; Chen, S.C., (2017). The study of consumer green education via the internet of things with green marketing. Eurasia J. Math. Sci. Technol. Edu., 13(9): 6133-6145 **(13 pages).**

Turró-Noa, A., (2023). Los Objetivos de Desarrollo Sostenible y el profesional de Ciencias de la Información. Ciencia and Futuro. 13(3): 503-514 **(12 pages).**

UN, (2015). Objetivos de Desarrollo Sostenible . Obtenido de Organizacion de las Naciones Unidas.

Unceta, K., (2014). Desarrollo, postcrecimiento y Buen Vivir: Debates e interrogantes. Editorial Abya-Yala **(197 pages).**

Wackernagel, M.; Rees, W., (1996). Our Ecological Footprint. New Society Publishers **(176 pages).**

Wang, Y.P., (2016). A study on Kinmen Residents' perception of tourism development and cultural heritage impact. Eurasia J. Math. Sci. Technol. Edu., 12(12): 2909-2920 **(12 pages).**

Wang, H.; Bao, C., (2021). Scenario modeling of ecological security index using system dynamics in Beijing-Tianjin-Hebei urban agglomeration. Revista Ecol. Ind., 125: 220-240 **(21 pages).**

AUTHOR (S) BIOSKETCHES

Zapata-Stacey, R., Ph.D. Candidate, Department of Civil and Environmental Engineering, Universidad de la Costa, Barranquilla, Colombia.
- Email: *rzapata8@cuc.edu.co*
- ORCID: 0009-0006-4490-0299
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://www.researchgate.net/profile/Ricardo-Zapata-Stacey?ev=hdr_xprf

Pinto Osorio, D., Ph.D., Professor, Dean of the Department of Civil and Environmental Engineering, Universidad de la Costa, Barranquilla, Colombia.
- Email: *dpinto3@cuc.edu.co*
- ORCID: 0000-0002-1496-5722
- Web of Science Researcher ID: NA
- Scopus Author ID: 56017822200
- Homepage: https://www.researchgate.net/profile/Diana-Pinto-Osorio

Rodríguez-Nieto, C.A., Ph.D., Professor, Department of Natural and Exact Sciences, Universidad de la Costa, Barranquilla, Colombia.
- Email: *crodrigu79@cuc.edu.co*
- ORCID: 0000-0001-9922-4079
- Web of Science ResearcherID: NA
- Scopus Author ID: 57217995167
- Homepage: https://www.researchgate.net/profile/Camilo-Rodriguez-Nieto?ev=hdr_xprf

AUTHOR (S) BIOSKETCHES

Machado-Penso, M., Ph.D., Professor, Universidad Tecnológica Metropolitana, Dieciocho 161, 8330383 Santiago, Región Metropolitana, Chile.
- Email: *mmachado@utem.cl*
- ORCID: 0000-0001-8727-3666
- Web of Science ResearcherID: NA
- Scopus Author ID: 8453636500
- Homepage: https://inesgenero.utem.cl/investigacion/nuestras-investigadoras/maria-veronica-machado-penso/

HOW TO CITE THIS ARTICLE

Zapata-Stacey, R.; Pinto Osorio, D.; Rodríguez-Nieto, C.A.; Machado Penso, M., (2025). Mathem atical model of the territorial bioecological coefficient to evaluate the progress of the sustainable development goal. Global J. Environ. Sci. Manage., 11(2): 805-824.

DOI: 10.22034/gjesm.2025.02.24

URL: https://www.gjesm.net/article_721918.html



Global J. Environ. Sci. Manage. 11(2): 825-856, Spring 2025, Serial #42

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

REVIEW PAPER

A global perspective on sustainable pathways for biogas adoption

K. Biró[1], K.S. Woon[2,3], W. Ounsaneha[4], C. Rattanapan[1,*]

[1]*ASEAN Institute for Health Development, Mahidol University, Nakhon Pathom 73170, Thailand*

[2]*School of Energy and Chemical Engineering, Xiamen University Malaysia, Malaysia*

[3]*Carbon Neutrality and Climate Change Thrust, Hong Kong University of Science and Technology, Guangzhou, China*

[4]*Faculty of Science and Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage, Klong Nuang, Klong Luang, Pathumthani 13180, Thailand*

ARTICLE INFO

Article History:
Received 13 October 2024
Revised 19 December 2024
Accepted 22 January 2025

Keywords:
Barriers
Biogas adoption
Influencing factors
Sustainability

ABSTRACT

Biogas technology has been developed worldwide in recent decades to provide affordable, secure, and clean energy in rural and developing regions. The technology presents various advantages, as it can be utilized for heating, generating power, and functioning as both a fuel and a raw material in the chemical manufacturing process. However, its widespread adoption remains hindered by complex social, economic, and environmental challenges. Local acceptance is increasingly becoming a critical factor for biogas projects and the transition to renewable energy. The objective of this systematic review is to explore and assess the diverse factors that contribute to the acceptance of biogas, utilizing publications from the Scopus, Web of Science, and PubMed databases for analysis. The study examined the connections among authors, disciplines, and geographic regions to contextualize the findings within the global framework. A visualization of similarities and Java-based software was utilized to map the trends in co-authorship, keyword co-occurrence, and thematic developments from 2013 to 2024. Adopting the preferred reporting items for systematic reviews and meta-analyses methodology, 1,358 studies were screened, resulting in 20 peer-reviewed publications meeting the inclusion criteria. A total of 248 factors influencing the acceptance of biogas were identified and clustered along the three sustainability dimensions. Biogas projects are influenced by social, environmental, and economic factors in distinct ways depending on the country or region. The weight scores within each dimension were normalized and the overall score of the studies were calculated, allowing for a comparability of the studies. The finding reveals that social factors are the most significant determinants of biogas adoption, including public trust, procedural justice, and community involvement, accounting for 45 percent of the total. Financial aspects, including incentives, operational costs, and market conditions represent 31 percent. The remaining 24 percent was comprised of environmental factors that received the lowest overall scores, including emission reduction, resource compatibility, and land use impacts. This indicates that the environmental drivers are less emphasized than the other two dimensions. The study emphasizes the critical significance of local governance, the engagement of stakeholders, and the implementation of strategic communication in facilitating the uptake of biogas. Perceived benefits, equity in decision-making, and accessible financial mechanisms emerged as key enablers, while barriers included mistrust, lack of awareness, uneven decision-making, and cost constraints. The significance of tailoring strategies to local conditions is highlighted by regional disparities. In Europe, the focus is on policy alignment, stakeholder governance, and sophisticated infrastructure, whereas developing regions emphasize affordability, education, and resource accessibility. The study highlights the necessity of an integrated approach that considers social, economic, and environmental dimensions, providing actionable insight to ensure equitable and sustainable biogas implementation.

DOI: 10.22034/gjesm.2025.02.25

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NUMBER OF REFERENCES
121

NUMBER OF FIGURES
8

NUMBER OF TABLES
10

*Corresponding Author:
Email: *cheerawit.rat@mahidol.edu*
Phone: +(66) 2441 9040-3
ORCID: 0000-0002-1799-422X

Note: Discussion period for this manuscript open until July 1, 2025 on GJESM website at the "Show Article".

INTRODUCTION

Renewable energy sources have received increasing interest in recent years (Alberto Huerta-Reynoso et al., 2019; Venko, 2022) as the global fight against climate change, fossil fuel reduction, and the need for renewable energy sources (Razinkov et al., 2021). The development of biogas technology represents a significant advancement in the dual fields of waste management and biofuel production (Arthur et al., 2011; Achinas et al., 2017; Venko, 2022; IEA, 2023). The implementation of biogas technology enables energy generation and the creation of biofertilizers, while also delivering various social and environmental advantages (Ji-Quin and Nyns, 1996). Global demand for biogas and biomethane is expected to accelerate, and the International Energy Agency (IEA) estimates that it will increase by 30 percent (%) between 2024 and 2030 to reach 2,270 petajoule (PJ) per year by 2030 (IEA, 2024). When examining the distribution of biogas demand across countries and regions, the European Union (EU) ranks first, while China occupies the second position (IEA, 2024; European Biogas Association, 2024a). The combined production of biogas and biomethane was 21 billion cubic metres (bcm), according to 2022 data (European Commission, 2023). The updated European Biomethane map (European Biogas Association, 2024b) shows that 81% of biomethane capacity comes from plants in the EU, where growth has reached 37%. According to Eurostat data (Eurostat, 2024), 90% of the EU's natural gas demand was met by imports in 2023, but investment in biogas remains vital to reduce dependence on third parties. By tapping into the biogas potential of agriculture and livestock farming, the ALFA project facilitates the increased market uptake of Renewable Energy Systems. It assists livestock farmers in adopting biogas technology while helping to navigate the existing obstacles within the EU. A Decision Support Tool has been developed to calculate the potential benefits of biogas solutions tailored to the specifications of an individual's farm. The tool estimates the profitability, environmental, economic and social benefits of the farms (ALFA, 2024). The European Biomass Association has been producing annual Statistical Reports since 2007, providing an overview of the bioenergy situation in the EU Member States (European Biomass Association, 2017). Scarlat *et al.* (2015) outline the European Union's policy framework for renewable energy and analyze the biomass demand needed to meet the EU targets. Local acceptance is increasingly becoming a critical success factor for biogas projects and the transition to renewable energy. There is a rising volume of studies investigating the determinants of social and public acceptance regarding diverse energy technologies. Wüstenhagen *et al.* (2007) provide a definition for social acceptance that is relevant to this discussion. The study proposes a threefold perspective on social acceptance, integrating socio-political, community, and market considerations. It concluded that factors influencing socio-political and community acceptance are increasingly highlighted, and market acceptance has received the least attention. Wüstenhagen *et al.* (2007) highlighted that a successful policy requires the agreement of all stakeholders. According to Moula *et al.* (2013), it is important to consider social acceptance, which impacts the achievement of energy policy goals. The number of biogas plants is steadily increasing, especially in Asia (Mukeshimana *et al*., 2021). As noted by Xue *et al*. (2020), the biogas policy framework established in Europe offers an important model for the development of biogas in China and other countries across Asia. Compared to China, Indonesia is in a more difficult position to spread renewable energy technology (IESR, 2019). Situmeang *et al.* (2022) presented an overview of Indonesia's socio-technical and socio-economic barriers to biogas deployment. The most prevalent cause for the inability to establish biogas plants is the absence of financial resources, such as funding and loans. For a successful innovation strategy, it is imperative that government and businesses collaborate closely. Promoting biogas requires an increase in technical knowledge and the establishment of clear legislative objectives (Situmeang *et al.*, 2022). Despite biogas having a long history of use in various energy applications, as well as its potential for integration into biogas-based production, its overall contribution to the existing energy structure and its climate benefits remains modest, particularly in rural developing areas (Rahman *et al*., 2014; Surendra *et al*., 2014; Luo *et al*., 2024; Sumiyati *et al.,* 2024). A case study from India (Parikh and Parikh, 1977) examines the economic benefits of families using a biogas plant, the impact of adopting a biogas plant at the national level and the limiting factors. Insufficient governance, inadequate organizational

frameworks, and limited public engagement were recognized as factors contributing to the unsuccessful implementation. To address this, a uniform pricing policy for purchasing agricultural waste, gas, and fertilizer distribution was proposed (Parikh and Parikh, 1977). Gosling (1982) explored the potential of biogas production in Thailand to mitigate the effects of rising imported oil prices and deforestation due to the dual fuel crisis affecting rural populations. This study underscores the demand for cost-effective construction solutions and advocates for a greater focus on the application of biogas technology in rural settings, along with its integration into broader rural development initiatives.

Sustainability and socio-economic impact

Biogas production can reduce greenhouse gas emissions (Han *et al.,* 2008), reduce eutrophication and improve plant nutrient utilization (Lantz *et al.,* 2007). The study by Walekhwa *et al*. (2009) focused on identifying the factors that affect energy usage derived from biogas in households in Uganda. The results show that biogas adoption increases with decreasing the age of the household head, increasing household income, increasing the number of cattle, increasing household size, increasing male household heads, and increasing the cost of conventional fuels. Plieninger *et al*. (2006) examine bioenergy benefits for German farms. The production of bioenergy presents a fresh economic outlook, characterized by its seamless integration and the provision of various social advantages, including the generation of employment opportunities. At the same time, it pointed out that biomass production alone is not sustainable, and a complex sustainability assessment of different biomass technologies is needed. The advantages are contingent upon the scale of the biogas plant and the nature of biomass processing, whether centralized or decentralized (Domac, 2002). Nevertheless, advocates agree that it stimulates economic development in rural communities, facilitates job creation, and promotes innovative investment opportunities (Domac, 2002; Sims, 2003). Biogas can diversify agricultural production and provide farmers with a "livelihood" (Kromus *et al*., 2004). van der Horst (2007) examined the debate on the siting of renewable energy in the United Kingdom (UK) and identified the factors that need to be considered to understand why people are worried about new energy installations and how they express their concerns. Simultaneously, there exists a gap in understanding the dynamic and contextual relationships that affect public interest and the acceptance of renewable energy installations. The research simultaneously integrates equity theories into assessing factors influencing community acceptance of biogas projects. Several studies (Terwel *et al*., 2011; Mercer-Mapstone *et al.,* 2018) have found that trust is a social acceptance indicator. Soland *et al*. (2013) identify the factors that impact the local acceptance of biogas plants. The study revealed that local acceptance of biogas is quite strong in Switzerland. There is a significant relationship among the perceived benefits, associated costs, and the level of trust in the operator significantly influences the overall acceptance of the technology. The research highlighted that perceived outcomes and citizens' trust strongly influence local acceptance and that the perception of smog increases costs and reduces benefits and trust. An increasing number of researchers, notably Batel *et al*. (2013), are focusing on the social aspects of renewable energy technologies. However, social acceptability also includes environmental, economic and social aspects (Brohmann *et al.*, 2007). Alasti (2011) identified the socio-political, community and market acceptance as dimensions of social acceptance. The primary factors impacting this are inadequate information, uncertainties surrounding policies, the sustainability of bioenergy, the need for supply chain diversification, and competition from new sectors. Upham *et al*. (2015) presented an analytical framework for thinking about the social acceptance of energy technology. The energy technology adoptions were distinguished in the context-based classification framework: general (political, public, and stakeholder), community (local public, local stakeholder, and local political) and market (end-users, stakeholder, and political) acceptance. Numerous studies efforts have explored the inconsistency between advocating for renewable energy technologies and opposing energy initiatives within local communities. In the literature, this is referred to as the "not in my backyard" (NIMBY) syndrome (Wexler, 1996). The NIMBY is based on rational choice theory and assumes that citizens who support the switch to renewable energy do not have to face the impacts of renewable technology in their own "backyard" (Devine-Wright, 2005;

Devine-Wright, 2009; van der Horst, 2007; Soland *et al*., 2013). Devine-Wright (2005) reviewed existing research on public perceptions of wind energy, where public opposition is usually described by the NIMBY effect (Wexler, 1996). The investigation uncovered six determinants, such as socio-economic, communication, institutional, and political aspects, that shaped public perceptions regarding wind farms and renewable energy. The unavailability of multivariate statistical tools and cross-disciplinary frameworks hinders the systematic explanation of how these variables interrelate. The independent variables influencing public opinion on wind farms are not isolated but are linked through dynamic and context-dependent relationships.

Challenges and opportunities

Segreto *et al*. (2019) demonstrated the social acceptance of several bioenergy projects across the EU countries and identified and classified the main factors influencing public confidence. The study conducted by Dermont *et al*. (2017) delved into the political dimension of policymaking in relation to social acceptance, thereby providing further insights to the framework established by Wüstenhagen *et al.* (2007). Twyhues (2020) examined the factors influencing the general public's social acceptance of bioenergy. The data reveals that the level of awareness regarding bioenergy is somewhat limited in Germany and the Netherlands. Nevertheless, the German citizens are more informed and exhibit a more optimistic perspective on bioenergy, largely due to the implementation of effective policy initiatives. Researchers (Thanh Truc *et al*., 2016; Ortiz *et al*., 2017; Gabisa and Gheewala, 2019; Haseeb, 2019; Sarker *et al*., 2020) identified several factors that influence the acceptance and adoption of biogas technology. A notable research gap exists due to the lack of uniformity in digester design and the inadequate examination of economic incentives that impact the adoption of biogas in diverse settings. One key factor is the availability of government subsidies or financial support, which can help individuals and institutions overcome the initial cost barriers associated with acquiring biogas digesters or plants (Osei-Marfo *et al*., 2018). Furthermore, the uniformity in digester design, along with the availability of maintenance and monitoring assistance, plays a vital role in ensuring the ongoing performance and effectiveness of biogas systems (K House *et al*., 2007; Nathalie Bachmann, 2013; Nsair *et al*., 2020). Another important aspect is the market value of the byproducts, such as bio-fertilizers, which can further enhance the economic viability of biogas projects and incentivize their adoption (Miltner *et al*., 2017; Osei-Marfo *et al*., 2018; Velásquez Piñas *et al*., 2019; IEA, 2020). Public acceptance plays a vital role in the deployment of renewable energy technologies, and the introduction of new energy solutions is contingent upon the approval of the community (Bang *et al*., 2000; Kasperson and Ram, 2013). The uncertainty also plays a significant role in public opinion (Kasperson and Ram, 2013). Despite its significance, the impact of uncertainty and risk perception on the public's willingness to adopt renewable energy technologies is still not well-explored. It would be worthwhile to examine the ways in which uncertainty and perceived risks affect the public's acceptance of biogas initiatives. Indicators influencing public behavior are the availability of knowledge and information about new technologies, fear and concern about risks, perceptions of new technologies, and people's mindsets (Assefa and Frostell, 2007).

Social acceptance and strategic communication

Lack of communication with the local community is one of the main reasons for the public response to renewable energy development. There is a scarcity of studies examining the effect of communication strategies on the public acceptance of renewable energy initiatives (Kaldellis, 2005; McCormick, 2010; Fytili and Zabaniotou, 2017). The study additionally investigates the role of strategic communication in enhancing acceptance of biogas systems. However, the acceptance of new energy projects shows an increasing trend if the public is informed about the developments in time (Kaldellis, 2005). Fytili and Zabaniotou (2017) found that the lack of information and knowledge on bioenergy projects and fears of environmental concerns about emissions are responsible for low social acceptance. However, there is a limited understanding of how public awareness and knowledge influence the acceptance of bioenergy projects. The study emphasizes enhancing public awareness as a crucial factor in promoting the biogas adoption. Farstad *et al.* (2024) investigated the socio-cultural conditions for the social acceptance of the bioeconomy through a case study in Norway.

Various elements of this study are aligned with the triangle model adapted from Wüstenhagen *et al.* (2007). Identification of socio-cultural factors influencing the adoption of bioeconomy projects and insufficient knowledge of trust in public authorities. Additional investigation is required to explore the socio-cultural aspects, particularly emphasizing trust as a vital element influencing biogas adoption, which is connected to the current study. Social acceptance is also influenced by awareness of climate change and technologies and perceptions of the fairness of decision-making processes (Fytili and Zabaniotou, 2017). There are various approaches to the concept of acceptance in different disciplines. Gareiou *et al.* (2020) highlighted the social acceptance of renewable energy sources as a critical factor for developing and deploying the projects. Zabaniotou (2018) offered an extensive analysis of the environmental, economic, and social aspects of bioenergy, aligning with the three pillars of sustainability. Innovation in electricity generation should consider food waste and residues as a feedstock. In the first scenario, effective management of supply chains and logistics plays a crucial role, whereas the second systems seem to be more sustainable due to the ease of redesigning small-scale operations. The research shows that a multidisciplinary approach combining the technical, economic, and social dimensions of bioenergy projects is lacking. In a study by Meidiana *et al*. (2020), the adoption of biogas in rural communities was investigated. The results revealed that key factors affecting farmers' choices to adopt biogas plants include their age, the size of their families, land ownership details, ownership of cows, and their knowledge about the technology. Sharpton *et al*. (2020) concluded that the distance of renewable energy plants from respondents' homes strongly influenced acceptance, as did the importance of economic considerations, environmental sustainability, and supply security. Respondents highlighted the understanding of utility providers and policymakers as a key influencing element. To ensure a comprehensive analysis of biogas acceptance, it is essential to incorporate socio-political dimensions, particularly emphasizing the minimum level of socio-political acceptance. Farstad *et al*., 2024 found a high level of trust in the authorities as a key condition. Furthermore, socio-political acceptance is also determined by people's lack of courage. The results of van Dijk *et al.* (2024) indicate that the acceptance depends on the type of biomass feedstock and the efficiency of the contribution to the energy transition. A recommendation has been made to focus more on the particular types of biomass feedstock that should be incorporated into strategic communication. Concerns regarding environmental and health impacts often obstruct the social acceptance of biogas. Paolini *et al.* (2018) provided estimates of the emissions of major greenhouse gases based on case studies from around the world. Biogas production can significantly reduce greenhouse gas (GHG) emissions but the research also draws attention to other emissions (Paolini *et al*., 2018). Public sentiment towards energy projects can be marked by significant negative emotions and resistance. Perlaviciute *et al*. (2018) focused on appropriately managing these emotional reactions. It was concluded that a value-based approach can identify public concerns about new energy projects, which help them respond effectively and adaptively and make responsible decisions (Haidt, 2001; Roberts, 2001; Roeser, 2011). There is a diversity of perspectives among individuals regarding the characteristics of energy projects that they prioritize and the level of acceptability they assign to different energy initiatives (Bidwell, 2013; De Groot *et al*., 2013; Perlaviciute and Steg, 2015). Despite a steadily increasing number of literature and projects on biogas technology adoption, significant gaps remain in understanding the interaction between economic, social, and environmental factors within a comprehensive and multidimensional sustainability framework. Current studies are constrained in their ability to systematically investigate these dynamics due to the insufficient use of interdisciplinary and integrated approaches. While regional variations in acceptance and the role of governance and stakeholder engagement have been highlighted, the integration of localized socio-economic and cultural contexts with global policy implications is underexplored. This study seeks to explore the various multidimensional factors that influence the acceptance of biogas production, based on the observations presented. It categorizes them according to sustainability dimensions to provide an integrated approach to ensure equitable and sustainable implementation of biogas. The current study was carried out in Thailand in 2024.

METHODOLOGY

This systematic review analyzes the factors that contribute to the acceptance of biogas production. The study design followed the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement (Moher *et al*., 2009; Page *et al*., 2021) to ensure methodological rigor and reproducibility (Soleas, 2021; Danya *et al.,* 2024; Torres-Ceron *et al*., 2025). Three primary research questions guided the study: 1) What significant factors influence local acceptance of biogas production? 2) What research methods (qualitative or quantitative) are used to explore the social acceptance of planned and existing biogas projects? 3) How can the factors determining local acceptance be classified?

Data extraction and screening process

A comprehensive literature search was carried out in Scopus, Web of Science (WoS), and PubMed databases between August and October 2024 to ensure the scientific quality of the research. The search conducted in the database aimed to explore the elements that influence biogas acceptance, employing five specific keyword combinations: “biogas”, “biomass energy”, “influencing factors”, “factors”, and “acceptance”, and using the “AND” and “OR” Boolean operators. All records were exported in a standardized tag format, specifically research information systems (RIS) into EndNote X9 software. Metadata, the 1,385 publications, contained authors’ details, publication year, title, journal, publisher, DOI, keywords, abstract, language, and document type. The screening was implemented in a two-phase approach. In the first initial screening, 39 duplicates were removed from the EndNote library, and 1,346 records underwent title and abstract screening against predefined exclusion criteria, resulting in the exclusion of 1,319 records due to irrelevance, unavailable of the full-text, publication year and type (e.g., books or grey literature), or non-English language.

In the second comprehensive review of the texts, 24 ambiguous records were carefully evaluated, leading to the identification of 20 studies that satisfied the inclusion criteria were selected for factor analysis. The selection process is illustrated in a PRISMA flow diagram (Fig. 1). This methodical approach guaranteed that only studies pertinent to the study questions and objectives were incorporated.

Publications were selected or excluded based on specific criteria, including the type of publication, the significance of biogas acceptance factors, the focus on sustainability, and the methodological robustness. Table 1 outlines the specific criteria in detail. The influencing factors identified from the selected studies were aggregated and categorized into three sustainability dimensions. This framework of dimensions offered a coherent structure for assessing

Table 1: Inclusion and exclusion criteria

Category	Inclusion criteria	Exclusion Criteria
Publication type	Peer-reviewed journal articles and review articles to ensure quality and validity.	Books, book sections, and conference proceedings.
Publication date	Publications published after 2013.	Publications before 2013.
Topic relevance	Publications investigating factors influencing biogas acceptance, adaptation, or perception.	Publications not focused on factors influencing biogas acceptance or adaptation.
Driving and barrier factors	Publications identifying or analyzing driving (promoting), or barrier (inhibiting) factors related to biogas.	Publications not analyzing driving or barrier factors related to biogas.
Language	English to ensure accessibility.	Non-English publications, even with English abstracts.
Geographic scope	Global publications focusing on regions where biogas is relevant for sustainability.	Publications focusing on regions where biogas has limited relevance or sustainability applications.
Methodology	Empirical studies, case studies, systematic reviews, and bibliometric analyses.	Non-research publications lacking empirical or systematic analyses.
Sustainability	Publications categorizing factors in at least one of the three sustainability dimensions.	Publications not categorize factors in any sustainability dimension.

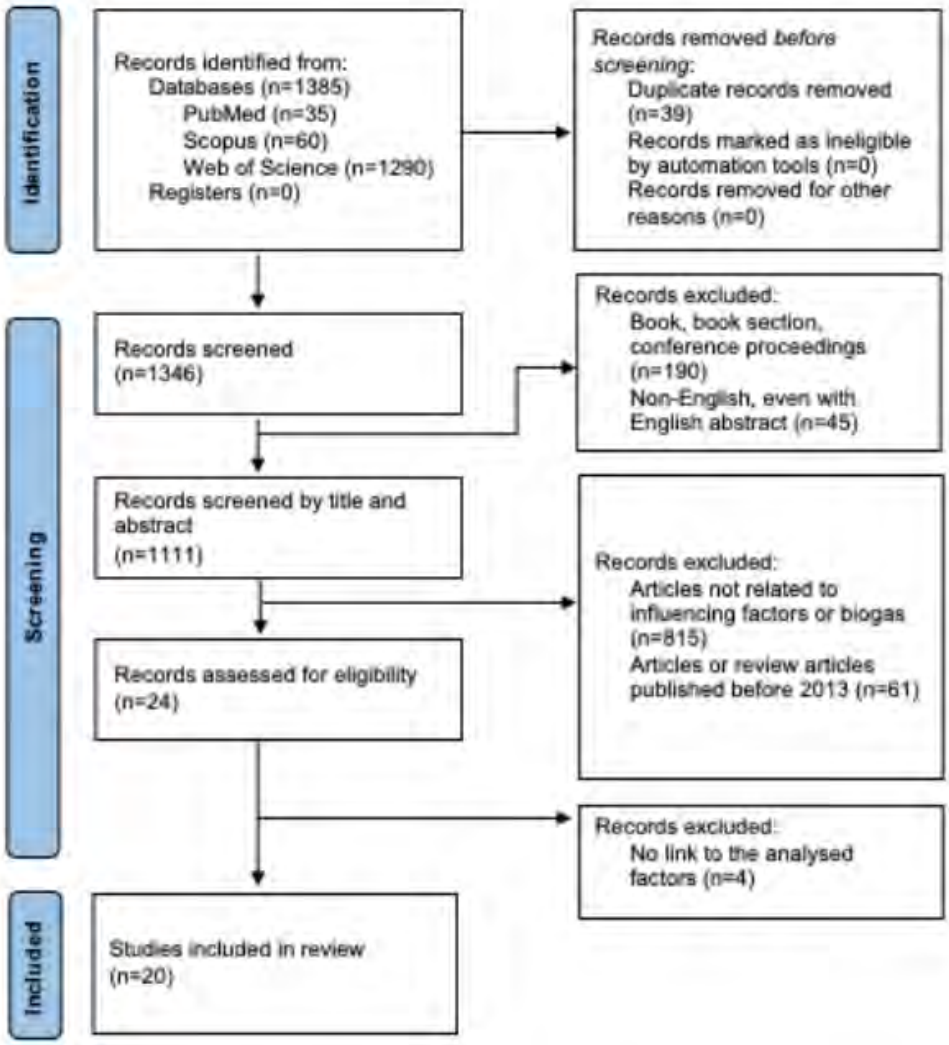


Fig. 1: PRISMA flow chart of the screening process to identify studies included in the review (Page *et al*., 2021)

Notes: The figure follows the PRISMA guidelines, detailing the steps of identification, screening, and inclusion, while also noting the reasons for study exclusions at each stage. A total of 1,385 records were retrieved from databases including PubMed, Scopus, and Web of Science. After removing duplicates (n=39) and applying inclusion criteria, 24 studies were assessed for eligibility. Ultimately, the analysis incorporated 20 studies that examined the various factors affecting the adoption of biogas technology.

the factors that impact biogas acceptance and their varying importance in different research contexts.

Bibliometric Analysis

Bibliometric analysis complemented the systematic review by using a visualization of similarities (VOS) Java-based software (VOSviewer) to construct and visualize bibliometric networks. The analysis shed light on trends in various disciplines, the geographic spread of research, and how research evaluation has changed over time. The study analyzed the interconnections among authors, various disciplines, and different geographic regions, including Europe, Asia, and America, to better understand the findings in a worldwide context. By integrating systematic review and bibliometric analysis, this study offers a comprehensive understanding of the sustainability dimensions shaping biogas acceptance and their regional and methodological variations. In order to clarify the significance of the factors involved, all studies were reviewed with respect to both the frequency and depth of their analytical approach.

Studies were assigned scores reflecting their methodological rigor and coverage of influencing factors:

- High weight (Score: 3): Studies employing comprehensive methods, such as multivariate or longitudinal analzses, and addressing multiple factors across all sustainability dimensions. These studies have explored the influencing factors and revealed a robust connection between the outcomes and the increased utilization of biogas.
- Medium weight (Score: 2): Studies using descriptive or single-method approaches (e.g., surveys, interviews) and addressing fewer factors.
- Low weight (Score: 1): Studies with limited focus, basic methods or a limited number of factors analyzed. Studies that concentrates on a narrow range of factors, such as solely social or environmental influences, or that depends on basic survey techniques without comprehensive statistical evaluation.

Normalization of the scores

To ensure that the studies could be compared effectively, the scores of the factors identified in the bibliometric analysis were normalized. This process allowed for an assessment of the weights of each sustainability dimension—environmental, economic, and social—relative to the maximum value found in the dataset. The normalization was performed using Eqs. 1 and 2 (Pollesch and Dale, 2016):

$$\text{Normalized score} = \frac{\text{Factor number}}{\text{Maximum factors in all studies}} \quad (1)$$

$$\text{Overall normalized score} = \text{Normalized environmental score} + \text{Normalized economic score} + \text{Normalized social score} \quad (2)$$

An elevated overall normalized score signifies a harmonious and meaningful contribution from the various sustainability dimensions, while a diminished overall normalized score points to a limited contribution across these dimensions.

RESULTS AND DISCUSSION

A total of 1,385 publications were identified in the comprehensive review. The search strategy identified 60 records in Scopus, 1,290 in Web of Science, and 35 in PubMed. After the selection process, the duplicates (n=39) were removed, and 1,326 publications were excluded based on the exclusion criteria. Finally, 20 publications were selected for the evaluation (Table 2). The first paper (Emmann *et al*., 2013) identifies the relevant influencing factors determining a biogas innovation's acceptability in 2013. In Fig. 2, the trend of publications and citations from 2013 to 2024 is presented. The bar graph illustrates the yearly number of publications, while the line graph tracks the corresponding citation counts.

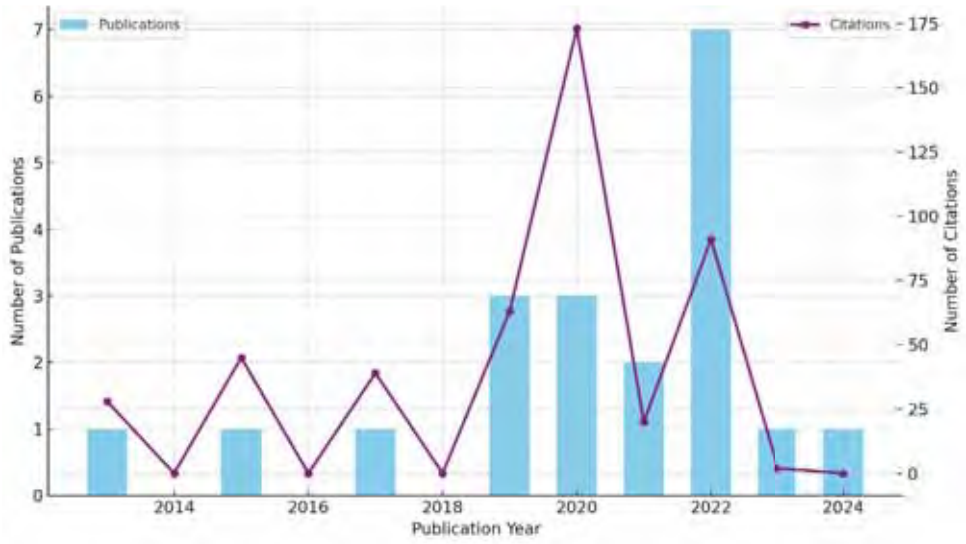


Fig. 2: Total publications and citations number (2013-2024)

Table 2: References focusing on identifying influencing factors of biogas acceptance

No.	Recruiting period	Objective	Factors			Unit of analysis	N	Method	Sources
			EN	EC	S				
1	Jun-July 2010	Determine factors influencing the acceptance of biogas innovation among farmers through causal analysis.	√	√	√	Households	180	Questionnaire survey	Emmann *et al.* (2013)
2	2009-2011	Analyze changes in public acceptance of biomass plants.	√	√	√	Households	423	Questionnaire survey	Kortsch *et al.* (2015)
3	Nov. 2014-Mar. 2015	Analyzing local acceptance of biogas plants in the Upper Rhine region and the influencing factors.	√	√	√	Households	433	Descriptive, multiple regression, GIS	Schumacher and Schultmann (2017)
4	July 2016-Feb. 2018	Examine the perspectives of biogas production stakeholders, identifying obstacles and levers for project development and exploring governance aspects of stakeholder interactions.	√	√	√	Stakeholders	55	Semi-structured interviews	Bourdin *et al.* (2019)
5	Dec. 2016	Analyze the relationship between spatial-economic variables and renewable energy source adoption in Poland.	√	√	√	Households	101	Statistical non-parametric: Spearman's rank correlation coefficient test	Hernik *et al.* (2019)
6	Sep.-Oct. 2013	Examine the public acceptance of hypothetical biogas plant (BGP) developments near residential areas in Germany.	√	√	√	Households	942	Questionnaire survey	Dobers (2019)
7	Oct. 2018	Assess household-based factors influencing the utilization of biogas generation technology.	√	√	√	Households	695	Descriptive and empirical; probit regression model-based estimations	Jabeen *et al.* (2020)
8	2003-2018	Analyse the success factors of anaerobic digestion projects in France.	√	√	√	Stakeholders	140	Quantitative: logit model (91); qualitative: semi-structured interviews (49)	Bourdin *et al.* (2020)
9	2001-2019	Assess factors affecting social acceptance of renewable energy systems in Europe.	√	√	√	Residents, stakeholders, experts	25	Comparative case studies	Segreto *et al.* (2020)
10	2018-2019	Argue for including the concept of naturalness in the social acceptance of renewable energy technology to address the social rejection of biogas technology.			√	Residents	607	Questionnaire survey and focus groups	Dumont *et al.* (2021)
11	NR	Establish key indicators for measuring green economy transition potential at the local level.	√	√	√	Residents	41	Domain-based approach, driving force–state–response (DSR) model, interviews (41)	Timonen *et al.* (2021)

Continued Table 2: References focusing on identifying influencing factors of biogas acceptance

No.	Recruiting period	Objective	Factors			Unit of analysis	N	Method	Sources
			EN	EC	S				
12	NR	Examine general and local acceptance of energy technologies by assessing public concerns, stakeholder trust, and attitudes.	√	√	√	Residents, stakeholders	1,247	Questionnaire survey	Baur *et al.* (2022)
13	2008-2020	Identifying critical challenges in realizing biogas projects.	√	√	√	Stakeholders	2,503	Multiple case studies (5), longitudinal analysis: documentum analyses (2,489), semi-7structured in8terviews (9)	Nielsen (2022)
14	2018-2021	Identify site-selection factors for biogas plants in Sweden under evolving conditions, emphasizing the need for spatially explicit analysis in decision-making processes.	√	√	√	Experts	34	Interviews (11), focus groups (2), reflexive thematic documentum analysis (21)	Feiz *et al.* (2022)
15	July 2021	Identifies factors influencing social acceptance of biogas plants.			√	NR	54	Systematic literature review	Mancini and Raggi (2022)
16	2008-2015	Identify critical non-technological success factors affecting centralized biogas project deployment.	√	√	√	Stakeholders	502	Longitudinal process analysis (1 case study, 408 documents), semi-structured interviews (3)	Nielsen *et al.* (2022)
17	NR	Examine household acceptance of bio-technology by categorizing driving and inhibitory factors.	√	√	√	Households	164	Questionnaire survey	Ahmed *et al.* (2022)
18	April-May 2018	Evaluate policy impacts and public perceptions of agricultural biogas plants in Slovakia, analyzing social acceptance in areas near residential zones.	√	√	√	Operators/experts, residents	239	Questionnaire survey (234) and interviews (5)	Kulla *et al.* (2022)
19	Sep.-Oct. 2022	Identify factors influencing household acceptance of biomethane generation technology in rural Pakistan.	√	√	√	Households	300	Logistic regression model, survey-based evaluation	Wu *et al.* (2023)
20	2012-2020	Explore regional factors influencing the establishment of biogas plants in 96 French regions.	√	√	√	Regional database	96	Empirical analysis	Coll-Martínez *et al.* (2024)

Notes: N: sample size; NR: not reported; EN: environmental; EC: economic; S: social.

The analysis shows changes in research productivity and academic engagement over the years, with distinct peaks observed in particular years. The graph depicts a temporal gap between the publication of works and their citation influence, indicating a slow process of gaining recognition. Overall, it indicates a shift in focus or interest within the academic field. From 2013 to 2018, the number of publications (Emmann *et al*., 2013; Kortsch *et al*., 2015; Schumacher and Schultmann, 2017) was consistently low, with no more than two publications each year. This timeframe signifies a phase of limited activity regarding the generation of new research findings. Throughout these years, citation levels remained low and inconsistent, experiencing modest increases in particular years, notably in 2015 and 2017. A slight rise in publications occurred from 2019, peaking significantly in 2022. Citations followed a fluctuating pattern with notable spinks in certain years. The rise in publications corresponds with the worldwide trend of increasing biogas production. A growing trend among countries is the investment in renewable energy sources, accompanied by efforts to diminish their dependence on fossil fuels. There is a significant rise in the trend across Europe and Asia, where agricultural byproducts and organic materials are being utilized to fulfill local energy needs.

The European Union greatly emphasizes biogas as it promotes sustainable agriculture and energy independence. Recently, China and India, two populous countries, have dedicated significant resources to the development of biogas infrastructure. China is now one of the world's largest biogas producers, primarily driven by agricultural and wastewater treatment projects. India is making significant strides in enhancing its biogas initiatives in rural regions to decrease reliance on firewood and fossil fuels. In the context of sustainability, advancing biogas production is among the climate and sustainability targets set by numerous countries. Subsidies and a favorable regulatory environment are helping biogas projects to take off, particularly in the European Union, where renewable energy sources are encouraged as part of energy policy objectives. Between 2019 and 2020, the number of publications nearly doubled (Bourdin *et al.* 2019; Hernik *et al*., 2019; Dobers, 2019; Jabeen *et al*., 2020; Bourdin *et al*., 2020; Segreto *et al*., 2020). The total number of citations jumped to 173 in 2020. This phenomenon indicates that research on biogas has had a significant impact and that biogas production is becoming an increasingly important renewable energy source, serving as a critical source of information for other research. The years 2020 and 2022 are notable for their significant citation and publication rates. These could be linked to groundbreaking research outcomes or areas that have unexpectedly surged in significance or interest among scientists.

Research areas

The publications on biogas acceptance identified in the Scopus, Web of Science, and PubMed databases cover nine disciplines, reflecting the multifaceted nature of the research topic. Investigations within this domain focus on the economic, environmental, social, and technological factors, thereby enriching the understanding of the various influences on public and institutional acceptance of biogas technology. Table 3 summarizes the primary research areas identified through the examination of publication trends, showcasing the interdisciplinary strategy essential for addressing the complex issues associated with biogas acceptance. "Environmental Science and Ecology" (40%) is the largest research area in biogas acceptance-related studies, highlighting the importance of ecological perspectives in understanding the technology's impacts and benefits. Studies within this domain analyze the impact of biogas adaptation on environmental sustainability, highlighting its contributions to lowering greenhouse gas emissions, improving waste management practices, and conserving valuable resources.

Representing 35%, the "energy and fuels" sector holds considerable importance, concentrating on the technical and operational features of biogas as a sustainable. Publications in this area usually assess the efficiency of biogas production, energy yield, and integration into existing energy systems. Also, "science and technology – other topics" (35%) represents an interdisciplinary approach to technological innovation. This field of study encompasses publications focused on new technologies, advancements in processes, and innovations across various sectors that improve the efficiency and viability of biogas production. "Business and Economics" (15%) plays a critical role in understanding the financial and market-driven aspects of biogas acceptance. Studies examine the cost-benefit ratios, market dynamics, and financial incentives

Table 3: Major research areas in references focusing on identifying influencing factors of biogas acceptance

Research area	TP	TP(%)
Environmental Sciences and Ecology	8	40%
Energy and Fuels	7	35%
Science and Technology - Other Topics	7	35%
Business and Economics	3	15%
Public Administration	2	10%
Public, Environmental and Occupational Health	2	10%
Geography	2	10%
Development Studies	1	5%
Engineering	1	5%

Notes: TP: total publications; TP(%): percentage of total publications.

that drive or hinder biogas adaptation. The selected publications analyze the economic viability of biogas-related projects from the perspective of households or businesses, shedding light on financial barriers and potential drivers that could increase adaptation rates. "Public Administration" (10%) deals with the policy and regulatory framework governing the introduction of biogas technology. Research emphasizes the importance of government initiatives in fostering biogas development by creating a supportive policy framework and implementing strategic regulatory actions. These studies underline the importance of policy coordination and administrative support in achieving widespread acceptance and operational success of biogas projects. "Public, Environmental and Occupational Health" (10%) examines the health implications of biogas production. Various publications analyze the health benefits linked to biogas, particularly its capacity to mitigate indoor air pollution resulting from standard cooking methods and the occupational health and safety issues faced by employees in biogas production plants. This field of study is crucial for recognizing and addressing health hazards, ensuring that biogas technology is both safe and advantageous for communities and individuals. "Geography" (10%) examines the spatial and regional factors influencing biogas acceptance, focusing on how geographical variables affect the uptake, implementation, and public perception of biogas projects. The researchers investigate the ways in which the presence of local resources, the density of the population, and land use patterns affect the practicality and acceptance of biogas technology in diverse areas. The geography studies provide valuable insights into regional differences in adoption, suggesting that biogas deployment strategies should consider local geographic characteristics to improve adoption rates. "Development Studies" (5%) examine the acceptance of biogas from a social development perspective, especially in low- and middle-income countries. This part focuses on the potential of biogas technology to contribute to sustainable development goals, particularly in terms of increasing energy accessibility in rural communities, bolstering economic resilience, and elevating quality of life standards. Researchers explore the role of biogas in supporting development initiatives by providing affordable, clean energy solutions for disadvantaged populations. Finally, "Engineering" (5%) deals with the technical design and infrastructure challenges related to biogas systems. Engineering research focuses on system design, optimization, and innovation and addresses practical issues related to the construction, efficiency, and maintenance of biogas plants. The study of engineering is essential for tackling the technical obstacles that hinder the scalability and reliability of biogas technologies, guaranteeing that biogas systems comply with both performance and safety requirements. The interdisciplinary nature of biogas acceptance highlights the complex interplay of environmental, technical, economic, social, and regulatory factors that influence acceptance by the public and institutions. Different fields of research contribute unique insights and solutions, emphasizing the importance of a unified approach that brings together diverse expertise to effectively address the multifaceted challenges related to the implementation of biogas technology.

Journals analysis

Studies on the acceptance of biogas span multiple scientific disciplines, with findings published in various esteemed journals that cater to diverse

yet interconnected research fields. The five most essential journals are listed in Table 4. Each journal presents a unique angle, underscoring the multifaceted nature of research related to biogas utilization. Each of the five journals represents 10% and accounts for 50% of the cumulative percentage, covering half of the journals under systematic review. As a top-tier journal in the field of energy research, Energy Policy is widely recognized for its focus on studies related to policy, regulatory structures, and governance matters. Publications in Energy Policy analyzes the political aspects of fostering the future implementation of biogas-based gas production, concluding that it is essential to advocate for biogas technology in a manner that is both sustainable and environmentally friendly (Dobers, 2019).

Policymakers should carefully evaluate the impact of biogas production targets on other industries to prevent any adverse effects on food production when planning for expansion (Emmann *et al*., 2012; Emmann *et al*., 2013). The Journal of Cleaner Production emphasizes sustainability and the management of environmental issues. The publications place biogas in the broader context of sustainable development and cleaner production practices. Studies emphasize the environmental benefits of biogas, including waste reduction, emission control, and contribution to the circular economy. The impressive h-index of 309 reflects the frequent citation of articles in this journal, emphasizing the critical role and relevance of sustainability-oriented research in the acceptance of renewable energy. Hernik *et al.* (2019) analysed the connection between spatial-economic factors and renewable energy storage. Feiz *et al.* (2022) examined the factors influencing the site selection of biogas plants. Renewable Energy has a 250 h-index with a Q1 ranking. Recognized as a leading publication in renewable energy, this journal features research on diverse energy sources, including biogas. Studies on biogas adaption focus on the technical, economic,

Table 4: Main journals focusing on the identification of factors influencing the acceptance of biogas in references

No.	Journals	TP	TP(%)	Cumulative frequency	Cumulative percentage	h-index	Quartiles
1	Energy Policy	2	10%	2	10%	272	Q1
2	Journal of Cleaner Production	2	10%	4	20%	309	Q1
3	Renewable Energy	2	10%	6	30%	250	Q1
4	Energy Research and Social Science	2	10%	8	40%	113	Q1
5	International Journal of Environmental Research and Public Health	2	10%	10	50%	198	Q2
6	Global Journal of Environmental Science and Management	1	5%	20	100%	33	Q1

Notes: TP: total publications; TP(%): percentage of total publications; h-index: Hirsch-index.

Table 5: Top-cited articles in references focusing on identifying influencing factors of biogas acceptance

No.	Total citations	Citation from this year	Countries\regions of the corresponding author	Sources
1	110	2013	Europe	Segreto *et al.* (2020)
2	52	2021	China	Jabeen *et al.* (2020)
3	45	2016	Germany	Kortsch *et al.* (2015)
4	40	2022	Germany	Baur *et al.* (2022)
5	39	2017	Germany	Schumacher and Schultmann (2017)
6	28	2014	Germany	Emmann *et al.* (2013)
7	23	2020	Germany	Dobers (2019)
8	21	2019	France	Bourdin *et al.* (2019)
9	19	2020	Poland	Hernik *et al.* (2019)
10	17	2022	Pakistan	Ahmed *et al.* (2022)

and environmental performance of biogas systems, exploring socioeconomics, infrastructural, and demographic factors, which are the critical factors of biogas generation technology utilization (Jabeen *et al*., 2020). The study by Kortsch *et al*. (2015) explored the various factors that impact public acceptance of biomass power plants, shedding light on the influences surrounding bioenergy project approval. Energy Research and Social Science represent 10% of the publications on factors influencing the acceptance of biogas, with a 113 h-index. The research explores the impact of social factors, including the level of public awareness, cultural acceptance, and community participation, on the adaptation processes of biogas plants (Dumont *et al*., 2021; Mancini and Raggi, 2022). Despite having a lower h-index compared to the aforementioned journals, its concentration on the social and human factors influencing renewable energy acceptance is essential for the effective implementation of biogas initiatives. The International Journal of Environmental Research and Public Health focuses on environmental and public health issues. In the context of biogas adoption, research in the journal focuses on the health benefits of biogas production, such as reduced indoor air pollution and improved public health, social equity (Timonen *et al*., 2021), as well as occupational health aspects for biogas plant workers. The journal's Q2 ranking and relatively high h-index (h-index=198) reflect its reputation for public health research, indicating that health-related factors are essential to biogas adoption research. The main journals - Energy Policy; Journal of Cleaner Production; Renewable Energy; Energy Research and Social Science; International Journal of Environmental Research and Public Health and Global Journal of Environmental Science and Management provide a unique perspective on the factors influencing the acceptance of biogas. Their high h-indexes and rankings in Q1 or Q2 reflect the substantial scientific contribution and diverse interdisciplinary nature of this research area. These journals highlight the multifaceted nature of biogas acceptance studies, including policy, social science, environmental impact, technical performance, and health aspects. This range illustrates the multifaceted challenges of biogas adoption, which depends on several key factors to facilitate its wider implementation in different sectors and communities.

Citations

In Table 5, the essential factors impacting biogas adoption are examined, including regional dynamics, household aspects, and social or territorial governance challenges, which represent the most commonly cited literature in the systematic review.

Segreto *et al.* (2020) analyzed the prevailing trends in accepting renewable energy in different European countries, including biogas. The evaluation focuses on the dynamics of social acceptance and details the cultural and political influences that shape the integration of renewable energy systems. Influencing factors include public perception, environmental benefits, economic incentives, policy frameworks, and community involvement. Additionally, the research examines the differences present among European countries, attributing these variations to regional policy differences, historical energy frameworks, and social influences, which collectively illustrate the acceptance of such impacts at both the societal and community levels. Jabeen *et al.* (2020) focused on household-based factors in Pakistan that influence the use of biogas production technology, particularly in the Punjab region. They underscore economic considerations such as income brackets, the accessibility of affordable biogas technologies, and the importance of education, and awareness. Factors such as social norms, family size, and the extent to which regions depend on conventional energy sources play a significant role in influence adoption. In addition, factors specific to Pakistan, such as infrastructural and political constraints, pose challenges to widespread adoption. The longitudinal study (Kortsch *et al.,* 2015) examined long-term trends in the acceptance of biomass, including biogas plants in Germany. The elements that play a role in this context include the economic benefits to the local community, the availability of employment, and worries about the potential environmental consequences. The study finds that adaption fluctuates with changes in policy incentives and the visibility of economic benefits to local communities. The findings underscore how continuous engagement with the community is crucial for fostering enduring acceptance (Kortsch *et al.,* 2015). Baur *et al.* (2022) examined social acceptance of energy technologies as part of the wider energy transition in Germany. Factors influencing the acceptance of biogas

include its environmental benefits, the perceived impact on national energy objectives, and local economic incentives. The study finds relatively high acceptance of biogas when the technology is in line with Germany's ambitious goals but also highlights the importance of addressing community concerns about environmental and economic impacts at the local level. A comparative study (Schumacher and Schultmann, 2017) investigated cross-border factors influencing the acceptance of biogas plants in the Upper Rhine region. Significant factors encompass the differences in regional policies, the environmental advantages, and the cultural views on renewable technologies. The inconsistencies in national energy policies, subsidy structures, and public participation methods have contributed to diverse levels of adaptation within the three countries of the region. Schumacher and Schultmann (2017) revealed the need for harmonized regional policies to improve adoption rates. Emmann *et al.* (2013) used a structural equation model to assess individual adoption of biogas innovation, focusing on psychological and social factors related to perceived simplicity of use, awareness of environmental benefits, and personal attitudes toward the technology. The results demonstrate that greater awareness and constructive social influences have significantly boosted engagement, highlighting the essential nature of educational campaigns and the impact of positive peer relationships. The research addresses spatial factors that influence the acceptance of biogas, such as the proximity of plants to residential areas and the impact on the local landscape. Dobers (2019) found that concerns about noise, odor, and visual impacts reduce the acceptance when plants are located near densely populated areas. Local cultural attachment to landscapes also influences acceptance, suggesting that strategic siting of plants and design changes can improve public perception. Bourdin *et al.* (2019) examined how territorial governance influences the proliferation of biogas production across various regions in different regions of France. Essential components consist of regional governance systems, participation of local stakeholders and administrative challenges. The findings of the study indicate that regions where governance is effectively coordinated to align local, regional, and national energy goals experience higher acceptance rates, underscoring the significance of strong governance in facilitating biogas deployment. Hernik *et al*. (2019), focusing on eastern Poland, identified the cultural and economic variables that affect the adaptation of renewable energy sources, including biogas. The adaptation rate is higher when the economic benefits, like reduced energy costs and local job creation, are obvious. Cultural attachment to traditional practices and limited knowledge of the benefits of renewable energy are challenging. To increase the acceptance of alternative energy solutions in regions with deep-rooted traditional energy practices, such as Poland, it is essential to implement community-driven approaches and educational programs. In the case of Pakistan, Ahmed *et al.* (2022) researched the acceptance of biogas technology using a diffusion of innovation framework, emphasizing factors such as economic viability, observed utility, social influence and compatibility of biogas with existing practice. Results indicate that adaptation is hindered by financial constraints, limited infrastructure, and low awareness, while expected benefits (cost savings and environmental impact) can stimulate adaptation if properly communicated (Ahmed *et al.*, 2022). The foremost ten publications emphasize the multifaceted interactions of elements that shape biogas adaptation, which encompass economic incentives (economic dimension), governance and policy considerations, community participation, and cultural (social dimension) aspects. Regional variations are significant, with household-level economic and social considerations prominent in areas such as Pakistan, while European studies focus on policy harmonization and territorial governance. Areas related to biogas deployment that require further investigation include enhanced policy frameworks and innovative technologies. Specific contributions include new insights into policy harmonization or the impact of community-led initiatives. As noted by Wüstenhagen *et al.* (2007), the adoption of biogas is significantly bolstered by local ownership and collaborative decision-making, especially in the context of wind energy projects. Their research highlights that financial involvement from residents can foster greater community trust and improve the viability of such initiatives (Wüstenhagen *et al.*, 2007). The gap between national renewable energy targets and local project implementation needs to be addressed through an adaptive policy. France's new policy framework has led to an increase in wind

energy capacity. An essential component of the measures was the reassignment of administrative responsibilities for granting authorization for wind farm projects to the regional subdivisions and municipal authorities (Nadaï, 2007). Planning, siting and permitting policy framework of renewable energy are key factors in local policy. While social acceptance responds to issues and processes related to site selection, policy measures tend to focus on planning issues (Nadaï, 2007).

Bibliometric analyses

By importing the RIS files extracted from the EndNote library, the VOSviewer software was used to create network visualization maps describing co-authorship and co-occurrence links in the biogas-related literature. To depict the connections, two visualization methods were utilized: network visualization and overlay visualization, similar to the techniques described by Maphosa and Maphosa (2022). The visualization map usually contains one type of link, and each link has a strength indicated by a positive numeric value. A higher value indicates a stronger link (van Eck and Waltman, 2018). The "link strength" indicates, for example, how many links the five publications have in common (bibliographic linkage links), how many publications have been co-authored by five researchers (co-authorship links), how many publications in which five terms occur together (co-occurrence links). The articles are categorized into clusters, which correspond to items found on the map. It is essential to understand that each element is limited to a single cluster and does not necessarily address every aspects of the map.

Countries

The studies reviewed in the literature analysis focus on public and social acceptance, territorial decision-making, policy impacts, and success factors of projects in different countries and regions (Table 6). In Europe, the emphasis of studies has largely been on the acceptance by the public, the impacts at the regional level, and the governance of territories related to renewable energy projects. The case studies in Pakistan and South Africa focus on household and community acceptance, particularly socio-economic and cultural factors. In the Nordic region, which encompasses Denmark, Sweden, and Finland, investigations are centered on the challenges of settlement, the determinants of site selection, and the prospects of the green economy at various levels, including local and national.

Germany has the highest percentage of publications, followed by France, Pakistan, and Denmark. This distribution illustrates the key focus areas across different countries, with a notable emphasis on Germany, France, and Pakistan. This indicates that these countries are proactively investigating the adoption and integration of renewable energy technologies, especially in the realm of biogas. Each publication emphasizes the importance of social, economic and political dimensions in the adoption and uptake of biogas and renewable energy technologies tailored to the specific needs of each country or region.

Co-authorship analyses

The co-authorship visualization map of the selected 20 documents was performed using VOSviewer. This

Table 6: National or regional areas of the publications

Country/ region	TP	TP(%)	Publication
Germany	5	25	Dobers (2019)
Pakistan	3	15	Kortsch, *et al.* (2015)
Denmark	2	10	Baur *et al.* (2022)
Finland	1	5	Emmann *et al.* (2013)
France	3	15	Schumacher and Schultmann (2017)
South Africa	1	5	Wu *et al.* (2023)
Slovakia	1	5	Jabeen *et al.* (2020)
Poland	1	5	Ahmed *et al.* (2022)
Sweden	1	5	Nielsen (2022)
Europe (Regional)	1	5	Nielsen *et al.* (2022)
Global	1	5	Timonen *et al.* (2021)

Notes: TP: total publications; TP(%): percentage of total publications.

network map depicts the collaborative relationships among 11 authors in the biogas sector, focusing on their co-authorship connections. Each node represents an author, with larger nodes indicating authors with higher collaborative influence. The relationships between the nodes are depicted by lines, where thicker lines signify a greater degree or frequency of co-authorship. The total 62 number authors in my network are not connected. The largest set of connected authors consisted of 11 authors therefore this set of authors was visualized and divided into three distinct clusters, color-coded (Fig. 3). Ahmad *et al*. (2022) demonstrate strong ties to multiple clusters. The interactions between Ahmad *et al*. (2022) and authors from various clusters, including red and green, imply that they functioned as a link, promoting collaboration across different research teams.

Keyword co-occurrence analyses

Keywords are grouped into clusters based on their co-occurrence patterns, indicated by their positions and connected lines. From a total of 225 keywords, 20 have satisfied the criteria in the bibliometric analysis, as shown in Fig. 4, and represent three thematic domains. This keyword co-occurrences network visualization map highlights the interdisciplinary nature of biogas research and the importance of integrating the three dimensions for a comprehensive understanding. Table 7 illustrates the overall strength of the co-occurrence links for each of the 20 keywords. The keywords with the greatest total link strength were selected. The three clusters are the "environment and energy" (central area, red color), the "social acceptance and policy" (left side of the network, green color), and the "technical and scientific systems" (right side of the network, blue color). There are intersections among the clusters; for example, the topic of acceptance is examined in both environmental and economic settings, as well as within social and political realms, demonstrating a multidisciplinary approach to the studies on renewable energy. This may indicate the need to integrate social, technical, and political considerations in energy adaption and sustainability debates.

The "Environment and energy" related cluster focuses on cross-cutting issues in environmental sciences and renewable energies, focusing on adapting and understanding biogas, renewable and wind energy. Additionally, it covers the economic considerations linked to the adaptation and business implications of these technologies. The keywords

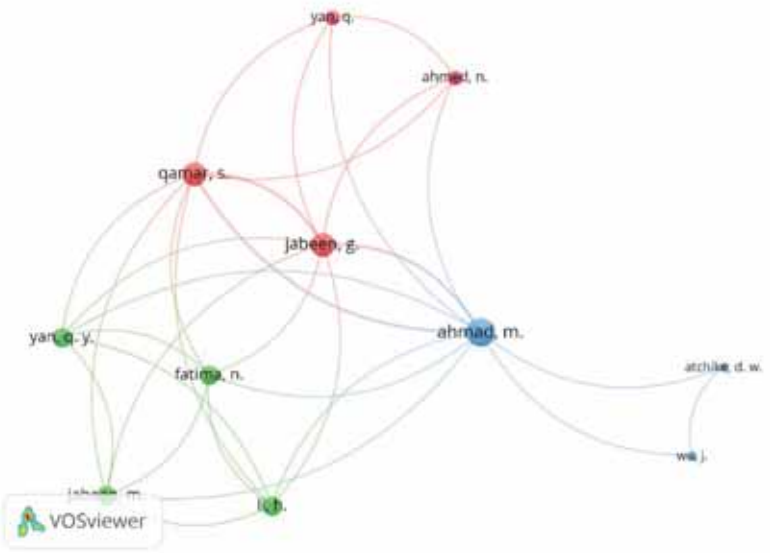


Fig. 3: Co-authorship collaboration network visualization to uncover the existing collaborations between authors contributing to biogas-related research minimum number of publications: 1)

Notes: red cluster: forms a tightly connected subgroup emphasizing specific themes in biogas research; green cluster: highlights another group with strong collaborative ties; blue cluster: centers on Ahmad et al. as a key bridging author linking diverse clusters.

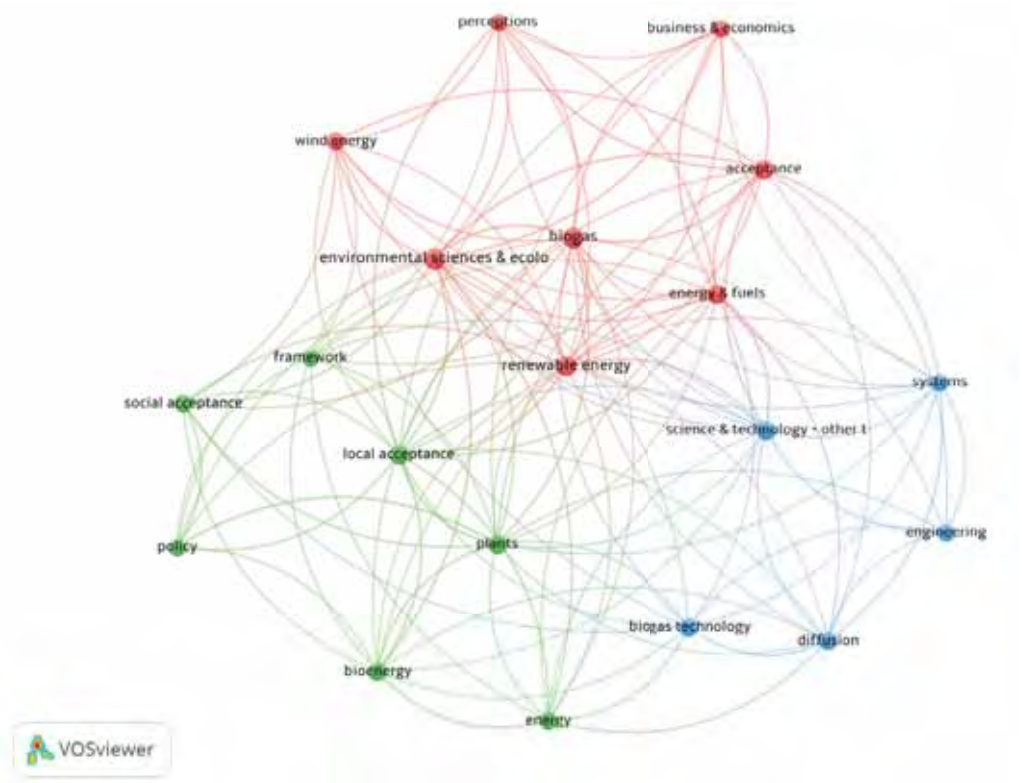


Fig. 4: Keyword co-occurrences network visualization illustrates the relationships between keywords used in biogas adoption studies (minimum number of occurencces of a keyword: 3)

Notes: The map groups keywords into three thematic clusters: (1) environment and energy (red) which focuses on renewable energy and environmental sciences; (2) social acceptance and policy (green) emphasizing social acceptance, frameworks, and policy; and (3) technical and scientific system (blue) covering engineering, diffusion, and biogas technology. The thickness of lines between nodes indicates the strength of co-occurrence between keywords, while proximity reflects thematic connections.

Table 7: Co-occurrences keywords and clusters (n=20)

Cluster No.	Thematic area	Keyword	Occurrences	Total link strength
1	Environment and energy	environmental sciences and ecology	8	36
		biogas	8	30
		renewable energy	7	29
		acceptance	6	30
		energy and fuels	6	28
		wind energy	4	16
		perception	3	17
		business and economics	3	15
2	Social acceptance and policy	local acceptance	6	30
		plants	6	26
		bioenergy	4	19
		energy	4	17
		social acceptance	4	15
		policy	3	12
		framework	3	11
3	Technical and scientific systems	science and technology – other topics	6	22
		diffusion	4	17
		biogas technology	4	15
		systems	3	13
		engineering	3	8

in cluster 1 refer to the general interest in the environmental and economic aspects of renewable energy, emphasizing social acceptance. This cluster, titled "Social acceptance and policy," is centered on the social acceptance and the policy frameworks that govern renewable energy and bioenergy. These keywords highlight the importance of social acceptance and policy. The studies examine the social and regulatory frameworks affecting the acceptance of renewable energy. The "Engineering and scientific systems" focuses on the scientific and technological aspects of renewable energy, with an emphasis on the technical challenges and advancements associated with biogas systems.

In conclusion, the keywords that co-occurrences refer to show patterns of how renewable energy research is interlinked. The key themes and relationships can be identified by analyzing which terms appear together frequently, such as the need for technological progress, social acceptance, and supportive policy frameworks for effective renewable energy adoption. The visualization of the co-occurrence network (Fig. 5) produced by VOSviewer demonstrates the frequency with which keywords appear together in publications related to biogas. The network map is color-coded according to the timeline of publications from 2019 to 2022, represented by a gradient color bar at the bottom of the image.

The network is presented in a chronological gradient, with colours ranging from purple (2019) to yellow (2022), showing when each topic came to the fore. Older themes (shades of purple/blue) are "perception", "business and economics" and "acceptance", indicating early debates focusing on social and economic impacts. More recent themes (shades of yellow) like "systems", "engineering", "diffusion" and "plants" indicate recent areas of interest in engineering and scientific research, reflecting a shift towards engineering-focused studies of renewable energy systems in later years. The co-occurrences network offers a glimpse into the relationships among related renewable energy themes, showcasing the ways in which social acceptance, environmental science, and engineering interact and affect each other. The chronological gradient highlights a transition in priorities: while initial studies primarily addressed social dimensions, there has been a recent trend towards a heightened interest in engineering and scientific progress.

Factors influencing biogas acceptance

In this study, a total of 248 factors have been selected and clustered according to the three dimensions of sustainability. Social, environmental, and economic

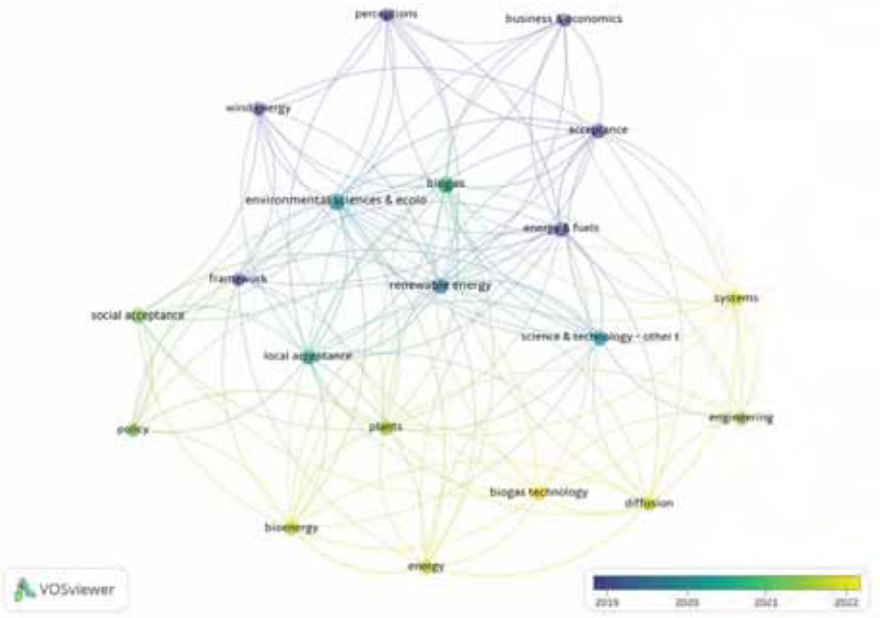


Fig. 5: Keyword co-occurrences overlay visualization (2019-2022)

factors affect the biogas project differently, depending on the country and region. The study conducted by Mukeshimana *et al*. (2021) focused on the barriers to biogas adoption in Rwanda, revealing that social acceptance is the foremost non-technical challenge facing the development of bioenergy initiatives. Rwanda has made significant efforts to promote biogas, particularly to meet rural energy needs and reduce dependence on conventional biomass. The key social factors were public awareness campaigns and educational programs. However, adoption has been hampered by cultural attitudes towards waste as a resource. While government subsidies have helped lower the initial financial burden for low-income families, the substantial maintenance costs still present a considerable obstacle. Biogas systems have contributed to better environmental and health conditions by decreasing deforestation and indoor air pollution. The rise in biogas production has been particularly notable in rural areas, where community-oriented strategies have built trust and promoted active participation among residents (Mukeshimana *et al.*, 2021). Mancini and Raggi (2022) concluded the same result and highlighted three critical factors for social acceptance, which can provide valuable insights into underrepresented regions like South America. Social trust is paramount, particularly in high-income regions, where community acceptance hinges on transparent communication, equitable benefit distribution, and localized governance. In low- and middle-income countries, the interplay of educational and socio-cultural factors, including the living conditions of women, plays a crucial role in determining levels of acceptance. This underscores the need to integrate educational campaigns and gender-sensitive approaches to foster support for biogas projects in rural areas. Biogas acceptance is highly dependent on local contexts. By embedding localized life cycle analysis and adapting project designs to cater to distinct regional demands, the likelihood of project adoption can be significantly increased (Mancini and Raggi, 2022). Mühl and de Oliveira (2022) identified three key dimensions influencing the development of anaerobic digestion (AD) technology in Brazil's agricultural sector: 1) Technological adaptation: Most AD plants in Brazil are small-scale, producing less than 500,000 normal cubic meter (Nm^3) of biogas per year. Tailored technological solutions that accommodate the small-scale nature of these units and their specific biogas applications, such as electricity generation, are crucial; (2) The biogas market is experiencing significant growth; however, there is an absence of cohesive policies and financial incentives to bolster the industry. Current regulations and subsidies are insufficient to drive large-scale adoption; (3) Regional and sectoral characteristics: The distribution of AD plants is concentrated in certain regions, particularly in the Southeast and South, highlighting the need for regional strategies and infrastructure development to expand AD's reach. The agricultural sector, despite its significant contribution to waste generation, produces only 11% of the total biogas, suggesting untapped potential (Mühl and de Oliveira, 2022). Oliveira *et al.* (2024) assessed biogas potential in Brazil, underscoring the sustainability of anaerobic digestion. Environmentally, AD offers significant benefits, including reduced emissions and enhanced waste management, particularly from cattle manure, food waste, and sugarcane residues. The economic analysis indicates a significant potential for renewable energy production, which could reduce natural gas demand by 10–22% and generate biofertilizers that exceed local agricultural requirements. Biogas production contributes to rural development by bolstering small-scale producers and cooperatives, thereby enhancing energy security and promoting sustainability in regions with dense populations. These findings emphasize the need for policy enhancements to unlock the region's biogas potential fully (Oliveira *et al.*, 2024). The development of biogas production in Colombia highlights critical socio-economic, technological and environmental dimensions (Rocha-Meneses *et al.*, 2023). From a socio-economic standpoint, it supports rural livelihoods, fosters job creation, and enhances energy independence, thereby encouraging sustainable growth. From a technological perspective, advances in anaerobic digestion and centralized biorefineries are increasing efficiency, although challenges such as high costs and limited infrastructure remain. From an environmental standpoint, the generation of biogas helps to decrease GHG emissions, supports sustainable waste management solutions, and presents environmentally-friendly alternatives, including organic fertilizers (Rocha-Meneses *et al.*, 2023). To determine which factors have had the highest impact on the acceptance of biogas, factors

that recur frequently in several studies within each dimension of sustainability were explored. The factors were structured into the three dimensions of sustainability to identify the most commonly emphasized dimensions. Fig. 6 illustrates the complexity of biogas deployment according to the key influencing factors identified along the three dimensions. Each category highlights essential elements necessary for sustainable and fair decision-making. The environmental factors emphasize the location of biogas plants, the associated environmental advantages and risks, such as pollution and odors, as well as the ecosystem resilience. These considerations underline the importance of assessing ecological impacts, like forest loss, emission levels, and the compatibility of projects with environmental policies and spatial planning rules. Other factors, such as heritage conservation and the availability of sustainable resources, underline the need to ensure environmental sustainability and long-term resource management.

The role of social factors underscores the significance of public endorsement, trust in governmental institutions, and the concepts of and procedural and distributive justice. Stakeholder engagement through community involvement, education, and transparent communication is critical to fostering social acceptance. Moreover, securing socio-political support, performing comprehensive risk evaluations, and ensuring just decision-making practices are vital for building trust and encouraging acceptance by local communities. Economic factors address the financial viability and economic benefits of projects. Key considerations include cost and profitability, energy market dynamics, and infrastructure feasibility. The importance of financing, subsidies, and resource efficiency cannot be overstated in achieving operational sustainability.

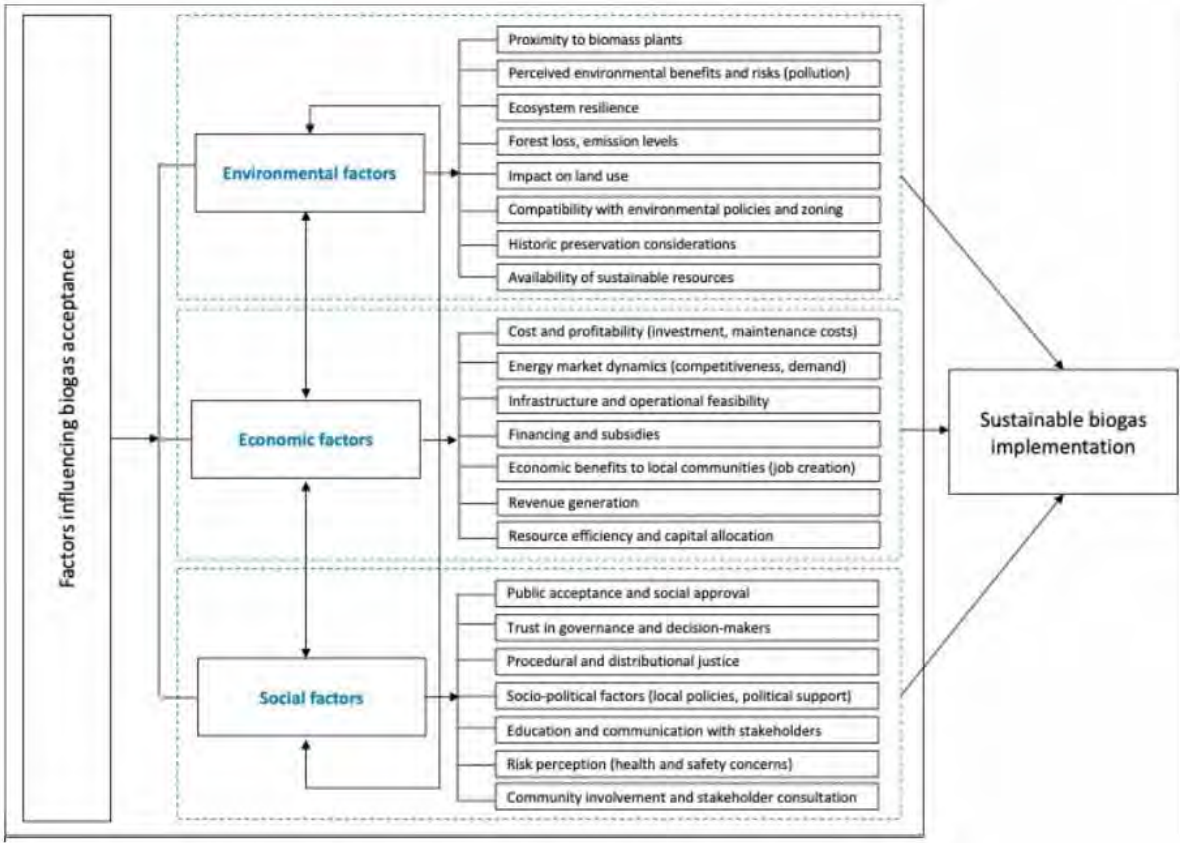


Fig. 6: Multidimensional model of biogas adoption and the relationship among the identified key influencing factors

Table 8: Ranking of key factors influencing biogas acceptance based on weighted analysis

Considerations of sustainability impact	Indicator No.	Methods	Weight	Weight score	Sources
Factors affecting success/failure of biogas projects	10	Quantitative and qualitative analysis	High	3	Bourdin *et al.* (2020)
Key factors in site selection for biogas plants	12	Interviews, focus groups, doc. analyses	High	3	Feiz *et al.* (2022)
Spatial-economic variables and renewable energy sources	21	Spearman's rank correlation	High	3	Hernik *et al*. (2019)
Diffusion of innovation factors for biogas acceptance	21	Questionnaire survey	High	3	Ahmed *et al*. (2022)
Success factors in centralized biogas project's lifecycle	30	Process analysis, interviews	High	3	Nielsen *et al*. (2022)
Regional determinants for biogas production setup	11	Empirical analysis	High	3	Coll-Martínez *et al*. (2024)
Longitudinal analysis of public acceptance of biomass plants	9	Questionnaire survey	High	3	Kortsch *et al.* (2015)
Territorial governance impacts on biogas projects	5	Semi-structured interviews	High	3	Bourdin *et al.* (2019)
Challenges and drivers for centralized biogas plants	18	Case studies, semi-structured interviews	High	3	Nielsen (2022)
Factors affecting biomethane technology acceptance	24	Logistic regression model	High	3	Wu *et al.* (2023)
Indicators for green economy and social acceptance	9	DSR model, interviews	Medium	2	Timonen *et al.* (2021)
Local acceptance in cross-national study	7	Multiple regression, GIS	Medium	2	Schumacher and Schultmann (2017)
Individual acceptance of biogas innovation	6	Structural equation model	Medium	2	Emmann *et al.* (2013)
Global factors influencing social acceptance of biogas	14	Systematic literature review	Medium	2	Mancini and Raggi (2022)
Household-based factors for biogas technology utilization	15	Probit regression model	Medium	2	Jabeen *et al.* (2020)
Public perception and policy impacts on biogas	11	Interviews	Medium	2	Kulla *et al.* (2022)
Social acceptance of energy technologies	10	Questionnaire survey	Medium	2	Baur *et al*. (2022)
Social acceptance and public involvement in Europe	8	Comparative case studies	Medium	2	Segreto *et al.* (2020)
Impact of spatial factors on biogas plant acceptance	6	Questionnaire survey	Medium	2	Dobers (2019)
Naturalness and social rejection factors	1	Questionnaire survey, focus groups	Low	1	Dumont et *al*. (2021)

Furthermore, economic benefits, including the creation of jobs and the generation of revenue, are vital for promoting community development. Integrating these factors emphasizes the importance of balancing short-term feasibility with long-term economic benefits. Table 8 presents an analysis of the factors frequently mentioned within each category. The studies are ranked according to their weight, with those marked "High" at the top. The weighted score is determined by the frequency and significance of the factors emphasized in each study, which are used to evaluate the quality of the publications. For the weighted analysis of the factors influencing the biogas acceptance, weighted scores were assigned based on how often each factor was mentioned in the studies, resulting in publications weighted by a score of 1 to 3. Factors that are mentioned more frequently were given a higher score. The assigned weight for publications indicates the overall quality and the rigor of the methodology employed in each study. The weight scores within each sustainability dimension were normalised, and the overall normalised score for the studies were calculated (Table 9) to allow a balanced comparison of studies.

The normalized score serves as an aggregate measure of the influence of all dimensions for each study, presented on a consistent scale. Figs. 7 and 8 illustrate a thorough comparison of how each study affects sustainability factors. In the case of Nielsen *et al.* (2022), four, and Wu *et al.* (2023), two "other" factors were also included in their study. The "other" factors include the "variety of size and continuity of use across seasons" or the "cooking time and fuel utilization". However, the present study focuses only on the environmental (EN), economic (EC), and social (S) factors; only the total normalized score obtained from these three aspects was calculated.

Fig. 7 highlights the contribution of environmental, economic, and social factors by authors. Nielsen *et al.* (2022) show a higher contribution in all dimensions, especially for environmental (EN) and economic (EC) factors. Certain scholars, including Mancini and Raggi (2022), concentrate on specific aspects, providing important insights into social factors. Fig. 8 illustrates the authors' overall normalized score. Nielsen *et al.* (2022) have the highest overall score, indicating a balanced and significant contribution across dimensions. Dumont *et al*. (2021) have a minimal

Table 9. Normalized comparison of sustainability dimensions across studies

N	EN	EC	S	Norm EN	Norm EC	Norm S	Overall norm	Sources
30	5	11	10	0.08	0.15	0.09	0.33	Nielsen *et al.* (2022)
24	2	5	15	0.03	0.07	0.14	0.24	Wu *et al.* (2023)
21	5	7	9	0.08	0.09	0.08	0.26	Ahmed *et al.* (2022)
21	10	9	2	0.17	0.12	0.02	0.31	Hernik *et al.* (2019)
18	3	7	8	0.05	0.09	0.07	0.22	Nielsen (2022)
15	2	6	7	0.03	0.08	0.06	0.18	Jabeen *et al.* (2020)
14	0	0	14	0.00	0.00	0.13	0.13	Mancini and Raggi (2022)
12	3	6	3	0.05	0.08	0.03	0.16	Feiz *et al.* (2022)
11	4	4	3	0.07	0.05	0.03	0.15	Coll-Martínez *et al.* (2024)
11	6	2	3	0.10	0.03	0.03	0.16	Kulla *et al.* (2022)
10	3	2	5	0.05	0.03	0.05	0.12	Baur *et al.* (2022)
10	1	3	6	0.02	0.04	0.06	0.11	Bourdin *et al.* (2020)
9	2	3	4	0.03	0.04	0.04	0.11	Kortsch *et al.* (2015)
9	4	1	4	0.07	0.01	0.04	0.12	Timonen *et al.* (2021)
8	2	1	5	0.03	0.01	0.05	0.09	Segreto *et al.* (2020)
7	2	2	3	0.03	0.03	0.03	0.09	Schumacher and Schultmann (2017)
6	3	1	2	0.05	0.01	0.02	0.08	Dobers (2019)
6	1	2	3	0.02	0.03	0.03	0.07	Emmann *et al.* (2013)
5	1	2	2	0.02	0.03	0.02	0.06	Bourdin *et al.* (2019)
1	0	0	1	0.00	0.00	0.01	0.01	Dumont *et al.* (2021)
248	59	74	109	-	-	-	-	

Notes: Factor counts: N (Total), EN (Environmental), EC (Economic), S (Social); Normalized scores: Norm_EN, Norm_EC, Norm_S, Overall Norm Score. In the case of Nielsen *et al.* (2022) four and Wu *et al.* (2023) two "other" factors were included in their study, but since the present study focuses only on the EN, EC, and S factors, only the total normalized score obtained from these three aspects was calculated.

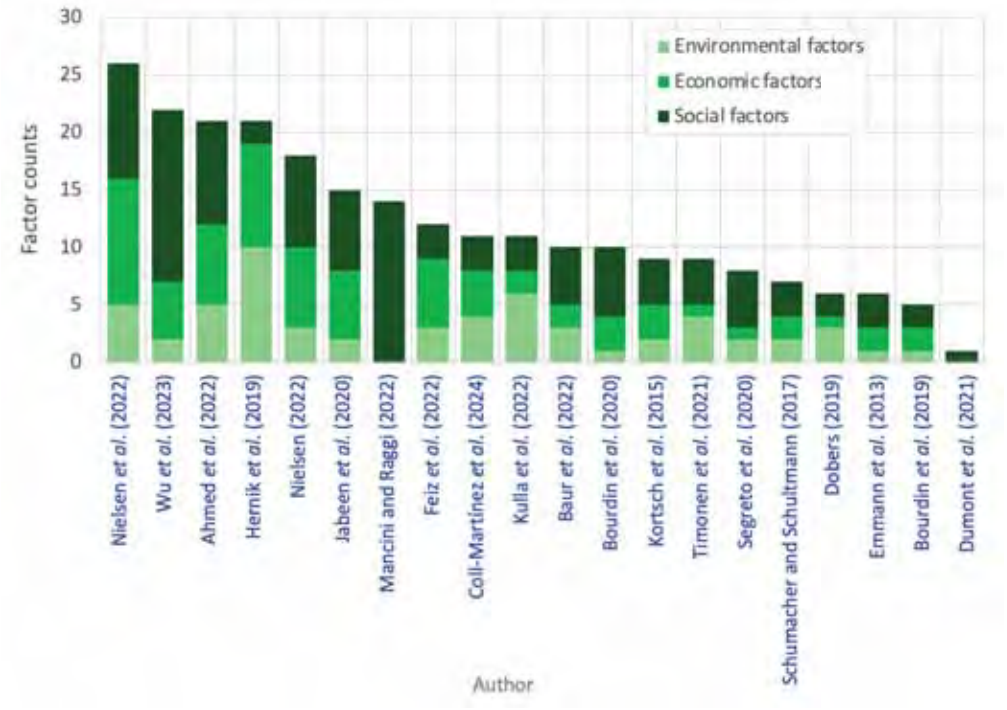


Fig. 7: Factor contribution by authors

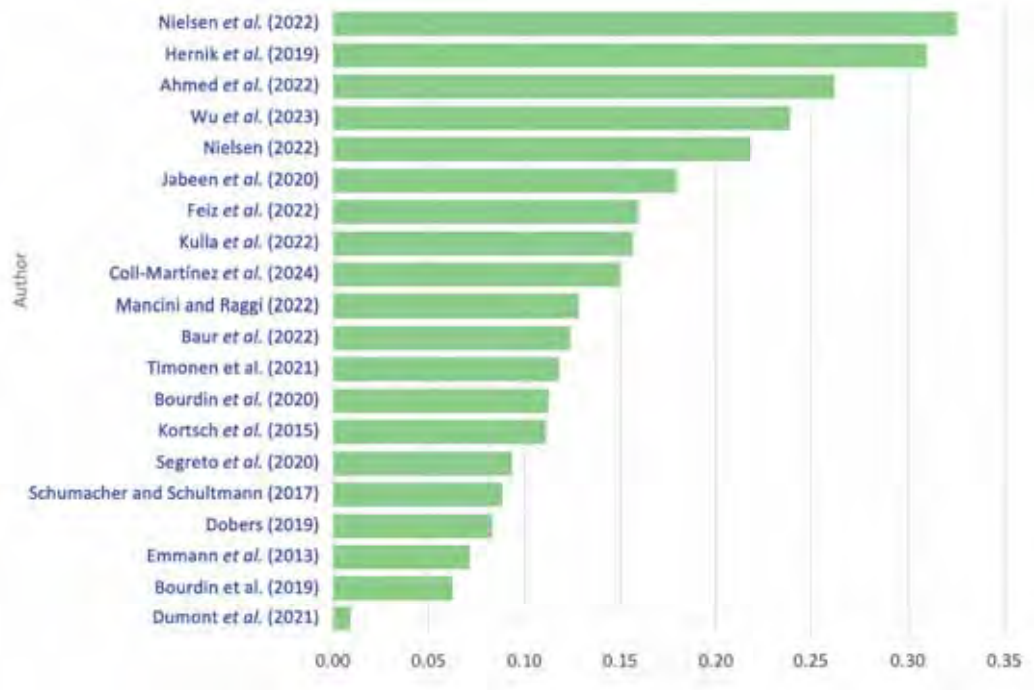


Fig. 8: Overall normalized scores by authors

Table 10: Distribution of the influencing factors in biogas adoption

Factors	Total No.	%	Max	Min	Average	Median	Standard deviation (SD)
Environmental	59	24.4	10	0	2.95	2.5	2.33
Economic	74	30.6	11	0	3.7	2.5	3.08
Social	109	45	15	1	5.45	4	3.95

overall normalized score, as their contribution across dimensions is low.

Many authors highlight a crucial trend where environmental and economic factors play a leading role. Social contributions are more variable, with some studies focusing on this aspect (Mancini and Raggi, 2022). The distribution of factors influencing the acceptance of biogas according to the three dimensions of sustainability shows that social factors dominate with 45%, followed by economic factors (31%), while environmental factors (24%) are the least prominent (Table 10). Although biogas production greatly diminishes GHG emissions relative to fossil fuels, it also introduces important ecological trade-offs that necessitate careful assessment to guarantee sustainable results. A large amount of fugitive methane (CH_4) is emitted from the biogas supply chain, during feedstock handling, anaerobic digestion, feedstock storage, and distribution can undermine its environmental benefits (IEA Bioenergy, 2019; Nisbet *et al.,* 2020). The digestate stage generated the most methane () which has a 27.2 ± 11 times greater global warming potential (GWP) than carbon dioxide (CO_2) over the 100-year horizon (IPCC, 2021). Methane emissions from the biogas supply chain surpass those from fossil fuels. Scheutz and Fredenslund (2019) conducted measurements of total methane emissions across 23 biogas plants located in Denmark. It was found that methane emission is between 0.4 and 15%, and the average emission from agricultural biogas plants is 2.4%. Biogas production could require substantial land for feedstock cultivation, storage, and infrastructure (Patinvoh and Taherzadeh, 2019; Jameel *et al.,* 2024). Focusing on the cultivation of specific energy crops for biogas may create competition with food production, contribute to deforestation, and threaten biodiversity. Furthermore, the use of digestate, which is produced through anaerobic digestion, as a fertilizer carries both benefits and potential risks (Chojnacka and Moustakas, 2024). While it enriches soil with nutrients, excessive or improper application can lead to nutrient runoff and water contamination. Biogas projects contribute to ecosystem services by reducing organic waste in landfills, mitigating landfill methane emissions, and recovering valuable resources (Obaideen *et al*., 2022). These projects need to be thoughtfully crafted to ensure they are in harmony with local ecological conditions and to mitigate potential negative effects, such as habitat disruption or over-extraction of biomass resources. Integrated planning that considers regional ecological sensitivities can optimize the environmental benefits of biogas systems. Economic factors show a slightly higher spread (standard deviation) than environmental factors, which implies that there is more variability in how they are identified in different publications. Environmental factors have the lowest overall average (mean) and total count, indicating that they are less emphasized than the other two dimensions.

Social factors have a higher maximum (15) than environmental factors (10), reflecting greater focus in certain studies. The minimum value for social factors is 1, while environmental factors have a minimum of 0, suggesting that some studies entirely omit environmental considerations. Social factors, with an average of 5.45, are notably more emphasized than environmental factors, which have an average of 2.95. This indicates a consistent trend of greater focus on social factors in various studies. The standard deviation for social factors is 3.95, surpassing the 2.33 standard deviation observed for environmental factors. This suggests that the identification of social factors varies more significantly across studies. Social factors dominate consistently in all metrics, showcasing a more substantial and widespread focus in research on biogas acceptance. Environmental factors are less frequently emphasized, with lower averages and a more minor total count, though their variability is narrower.

Recommendations and future direction

Biogas is increasingly becoming a key component of global renewable energy sources, therefore addressing the multidimensional challenges is essential to ensure its widespread deployment and long-term sustainability. By merging technological innovations, socio-economic aspects, and a solid policy framework, we can create an opportunity to boost the implementation of biogas technology. This requires tailored strategies that take into account local cultural, environmental and economic contexts while building on lessons learned from successful implementations worldwide. The following recommendations and future directions outline key actions and innovative approaches to maximize the uptake of biogas, optimize the environmental and social benefits and minimize the associated challenges. These strategies are designed to offer policymakers, stakeholders, and researchers valuable insights that can guide the evolution of biogas initiatives moving forward. Standardized requirements for biogas projects can reduce uncertainties in permitting processes and limit discretionary decisions that increase development risks. It is essential to recognize that the location and approval of renewable energy initiatives cannot be governed by a singular policy framework, as regional disparities in cultural, political, social, and environmental attributes exist. To address these challenges, a centralized "one-stop shop" permitting system is recommended to streamline approval processes. Clear guidelines for community participation are essential to incorporate local input into project siting and design phases, ensuring projects align with community needs and priorities. The role of governments is crucial in defining standards and ensuring that local ordinances do not impede or restrict the progress of project development. Having transparent permitting schedules and consistent deadlines can streamline the review and approval process, ultimately improving the chances of project success. Early community engagement and consistent communication are key to addressing local resistance, which often stems from concerns about land use and visual impacts. Direct, on-the-ground engagement with local communities fosters trust and mutual understanding, enabling companies to identify and address concerns during the flexible stages of project planning. From an ecological standpoint, it is crucial to formulate and execute robust methane reduction strategies at all levels of the biogas supply chain. Prioritizing the use of agricultural residues, organic waste, and manure as feedstock minimizes land-use conflicts and aligns with the principles of a circular economy. Policies should emphasize the use of non-food biomass to reduce ecological pressures. Investigating optimal practices for digestate management and the associated regulatory frameworks is crucial for reconciling the agricultural benefits of digestate with the possible environmental hazards. The ecological trade-offs of biogas adoption, such as methane leakage, land-use conflicts, water contamination, and resource over-extraction, require careful management to maximize benefits while minimizing harm. Addressing these challenges demands advanced technologies, robust policy frameworks, and proactive stakeholder engagement to achieve long-term ecological balance. Recognizing regional variations in adoption barriers, future strategies should integrate cultural, social, and economic contexts into global policy frameworks to create region-specific solutions. Recognizing the critical role of social factors, the implementation of participatory governance models is suggested to ensure that all stakeholders are fairly represented, which in turn promotes trust and acceptance of the project. Research should focus on innovative financial solutions such as community-based financing models, public-private partnerships, and subsidy optimization tailored to resource-constrained regions. Future studies should also examine the long-term impacts of stakeholder governance, particularly the role of third-party organizations, in building trust and ensuring equitable outcomes in biogas deployment. These coordinated initiatives will enhance the sustainable advancement of biogas as an effective renewable energy solution.

CONCLUSION

This study conducts a thorough analysis of the determinants impacting the acceptance of biogas, employing a systematic literature review and bibliometric analysis to highlight the sustainability dimensions of environmental, economic, and social factors. The results demonstrate the multidimensional complexity of biogas technology adoption, emphasizing the interplay between technical, social, and policy factors. Social factors are the most significant determinants of biogas adoption,

based on trust in governance, procedural equity, public involvement, and community-level benefits. Procedural equity emphasizes the importance of fairness in the decision-making procedures, ensuring that all relevant stakeholders have an equal opportunity to participate and articulate their concerns. Community-level advantages pertain to the beneficial impacts that biogas initiatives can provide to local populations. These benefits may include job creation during project construction, operation and maintenance and increased demand for local goods and services; improved access to clean and reliable energy that can increase energy independence and reduce dependence on fossil fuels; reducing air pollution and GHG emissions, which can lead to improved public health and environmental conditions in the community; community members can receive training in biogas technologies, leading to skills development and long-term career development; the improved infrastructure, such as roads or transmission lines, built as part of a project can benefit the wider community. The role of economic factors, such as financial incentives, subsidies, and operational costs, is vital in mitigating adoption barriers, especially in rural and developing regions. Financial incentives in biogas projects are designed to encourage development and deployment by reducing upfront costs, improving profitability, and ensuring long-term sustainability. Governments can provide direct financial support to cover a portion of the project's costs, like the equipment, construction, or infrastructure costs. Tax incentives facilitate the reduction of taxable income by allowing the deduction of investment costs or can provide tax benefits based on the quantity of energy produced from biogas. Fixed payments for biogas energy fed into the grid, ensuring a steady revenue stream. Government-backed or subsidized loans provide favorable terms for financing biogas projects, reducing financial risks for developers. Biogas projects that reduce GHG emissions can gain carbon credits on international or regional carbon markets and sell them for additional revenue. Incentive programs for energy efficiency recognize biogas initiatives for their contributions to lowering total energy usage or enhancing the effectiveness of waste-to-energy operations. Public-private partnerships (PPPs), can be set up to work with governments or other organizations to share costs, reduce risks and provide long-term support for project operations. Although less pronounced, environmental considerations play a pivotal role in assessing the ecological benefits of biogas, including emission reduction, waste management efficiency, and compatibility with environmental policies. Regional differences highlight the importance of adapting strategies to local circumstances. In Europe, policy harmonization, stakeholder governance, and advanced infrastructure dominate, while affordability, education, and access to resources are priorities in developing regions. Stakeholder management encompasses the proactive engagement of all pertinent stakeholders, including community members, government entities, developers, and external organizations, throughout the decision-making, project design, and implementation phases. The analysis underlines that the successful deployment of biogas depends on a balanced approach that integrates all three dimensions of sustainability. The systematic review and bibliometric analysis identify several critical factors, including transparent communication, participatory governance, and targeted financial mechanisms, as critical to promoting uptake. Conversely, barriers such as mistrust, lack of awareness, and uneven decision-making processes must be systematically addressed to achieve widespread adoption. In conclusion, biogas holds great promise as a sustainable energy alternative, as long as the strategies for its implementation are crafted to be inclusive, contextually suitable, and consistent with the tenets of environmental sustainability, economic viability, and social equity. Future research should focus on longitudinal and interdisciplinary studies to better understand evolving societal perceptions, economic trends, and environmental impacts, thereby ensuring that biogas systems contribute meaningfully to global renewable energy goals.

AUTHOR CONTRIBUTIONS

K. Biró was responsible for conceptualizing the draft, searching the bibliography, selecting the relevant references, coding the references, writing the initial manuscript draft, synthesizing the manuscript, and revising the final manuscript version. K.S. Woon was responsible for reviewing the whole manuscript and validating it. W. Ounsaneha was responsible for the project administration and resources. C. Rattanapan was responsible for reviewing the whole manuscript,

supervising the research, and responsible for the funding acquisition.

ACKNOWLEDGEMENT

This study is funded by the National Research Council of Thailand (NRCT) and Mahidol University, with the contract reference number [N42A670582].

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy, have been completely witnessed by the authors.

OPEN ACCESS

©2025 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit:

http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims with regard to published maps and institutional affiliations.

ABBREVIATIONS

%	Percent
AD	Anaerobic digestion
AEBIOM	European Biomass Association
ALFA	Scaling up the market uptake of Renewable Energy Systems by unlocking the biogas potential of Agriculture and Livestock FArming
bcm	Billion cubic metres
CH_4	Methane
CO_2	Carbon dioxide
DST	Decision Support Tool
EBA	European Biogas Association
EC	Economic
e.g.	Exempli gratia/for example
EN	Environmental
Eq.	Equation
EU	European Union
Fig.	Figure
GHG	Greenhouse gas
GWP	Global warming potential
h-index	Hirsch-index
IEA	International Energy Agency
IESR	Institute for Essential Services Reform
IPCC	Intergovernmental Panel on Climate Change
NIMBY	Not in my back yard
Nm^3	Normal cubic meter
NR	Not reported
PJ	Petajoule
PRSIMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PPS	Public-private partnership
RES	Renewable Energy Systems
RIS	Research Information Systems
SD	Standard deviation
S	Social
TP	Total publications
UK	United Kingdom
VOS	Visualization of similarities
WoS	Web of Science

REFERENCES

Achinas, S.; Achinas, V.; Euverink, G.J.W., (2017). A technological overview of biogas production from biowaste. Engineering. 3(3): 299-307 **(9 pages)**.

Ahmed, N.; Qamar, S.; Jabeen, G.; Yan, Q.; Ahmad, M., (2022). Systematic analysis of factors affecting biogas technology acceptance: Insights from the diffusion of innovation. Sustainable Energy Technol. Assess., 52: 102122 **(13 pages)**.

Alasti, E., (2011). IIIEE Master thesis IMEN41 20112. The International Institute for Industrial Environ. Econ. **(73 pages).**

Alberto Huerta-Reynoso, E.; Alfredo López-Aguilar, H.; Alberto Gómez, J.; Guadalupe Gómez-Méndez, M.; Pérez-Hernández, A., (2019). Biogas power energy production from a life cycle thinking. New frontiers on life cycle assessment - Theory and Application. IntechOpen. **(18 pages)**.

ALFA, (2024). Engagement platform. Biogas model, Program v. 1.

Arthur, R.; Baidoo, M.F.; Brew-Hammond, A.; Bensah, E.C., (2011). Biogas generation from sewage in four public universities in Ghana: A solution to potential health risk. Biomass Bioenergy, 35(7): 3086-3093 **(8 pages).**

Assefa, G.; Frostell, B., (2007). Social sustainability and social acceptance in technology assessment: A case study of energy technologies. Technol. Soc., 29(1): 63-78 **(16 pages).**

Bang, H.K.; Ellinger, A.E.; Hadjimarcou, J.; Traichal, P.A., (2000). Consumer concern, knowledge, belief, and attitude toward renewable energy: an application of the reasoned action theory. Psychol. Mark., 17: 449-468 **(10 pages).**

Batel, S.; Devine-Wright, P.; Tangeland, T., (2013). Social acceptance of low carbon energy and associated infrastructures: A critical discussion. Energy Policy, 58: 1-5 **(5 pages).**

Baur, D.; Emmerich, P.; Baumann, M.J.; Weil, M., (2022). Assessing the social acceptance of key technologies for the German energy transition. Energy Sustainable Soc., 12(1): 4 **(16 pages).**

Bidwell, D., (2013). The role of values in public beliefs and attitudes toward commercial wind energy. Energy Policy. 58: 189–199 **(11 pages).**

Bourdin, S.; Colas, M.; Raulin, F., (2019). Understanding the problems of biogas production deployment in different regions: territorial governance matters too. J. Environ. Plann. Manage., 63(9): 1655-1673 **(19 pages)**.

Bourdin, S.; Raulin, F.; Josset, C., (2020). On the (un)successful deployment of renewable energies: Territorial context matters. A conceptual framework and an empirical analysis of biogas projects. Energy Stud. Rev., 24(1): 4088 **(23 pages).**

Brohmann, B.; Feenstra, Y.; Heiskanen, E.; Hodson, M.; Mourik, R.; Prasad, G.; Raven, R., (2007). Factors influencing the societal acceptance of new, renewable and energy efficiency technologies: meta-analysis of recent European projects. Paper presented at European Roundtable for Sustainable Consumption and Production, Basel, June 20-22 **(18 pages).**

Chojnacka, K.; Moustakas, K., (2024). Anaerobic digestate management for carbon neutrality and fertilizer use: A review of current practices and future opportunities. Biomass Bioenergy. 180: 106991 **(23 pages).**

Coll-Martínez, E.; Labrouche, G.; Nadel, S.; Orozco, L., (2024). Regional determinants of biogas production units setup: Evidence from France. Papers Reg. Sci., 103(1): 100007 **(12 pages).**

Danya, U.; Kamaraj, M.; Suresh Babu, P.; Aravind, J., (2024). Bibliometric analysis and review of food waste management via sustainable approaches. Global J. Environ. Sci. Manage., 10(4): 2127-2144 **(18 pages)**.

De Groot, J.I.M.; Steg, L.; Poortinga, W., (2013). Values, perceived risks and benefits, and acceptability of nuclear energy. Risk Anal., 33: 307–317 **(11 pages)**.

Dermont, C.; Ingold, K.; Kammermann, L.; Stadelmann-Steffen, I., (2017). Bringing the policy making perspective in: a political science approach to social acceptance. Energy Policy. 108: 359-368 **(10 pages)**.

Devine-Wright, P., (2005). Beyond NIMBYism: Towards an integrated framework for understanding public perceptions of wind energy. Wind Energy. 8(2): 125-39 **(15 pages).**

Devine-Wright, P., (2009). Rethinking NIMBYism: The role of place attachment and place identity in explaining place-protective action. J. Community Appl. Soc. Psychol., 19: 426-441 **(16 pages).**

Dobers, G.M., (2019). Acceptance of biogas plants taking into account space and place. Energy Policy, 135(12): 110987 **(12 pages).**

Domac, J., (2002). Bioenergy and job creation. Unasylva, 211: 18-19 **(2 pages).**

Dumont, K.B.; Hildebrandt, D.; Sempuga, B.C., (2021). The yuck factor of biogas technology: Naturalness concerns, social acceptance and community dynamics in South Africa. Energy Res. Social Sci., 71: 101846 **(11 pages)**.

European Biogas Association, (2024a). Statistical Report 2024 **(72 pages).**

European Biogas Association, (2024b). European Biomethane Map 2024.

Emmann, C.H.; Arens, L.; Theuvsen, L., (2013). Individual acceptance of the biogas innovation: A structural equation model. Energy Policy. 62, 372-378 **(17 pages)**.

Emmann, C.H.; Theuvsen, L., (2012). Impact of biogas production on the regional land lease market - Empirical study of five rural districts in Lower Saxony with high density of biogas plants. Berichte Uber Landwirtschaft. 90(1): 84-112 **(19 pages).**

European Biomass Association, (2017). Statistical report. European bioenergy outlook. Key findings. European Biomass Association. 1-43 **(43 pages).**

European Commission, (2023). Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions. EU wide assessment of the draft updated National Energy and Climate Plans. Brussels, 18.12.2023, COM. 796 final **(22 pages).**

Eurostat, (2024). Natural gas supply statistics, May 2024.

Farstad, M.; Otte, P.P.; Palmer, E., (2024). Socio-cultural conditions for social acceptance of bioeconomy transitions: the case of Norway. Environ. Dev. Sustainable. 26(7): 18559–18574 **(15 pages)**.

Feiz, R.; Metson, G.S.; Wretman, J.; Ammenberg, J., (2022). Key factors for site-selection of biogas plants in Sweden. J. Cleaner Prod., 354: 131671 **(10 pages)**.

Fytili, D.; Zabaniotou, A., (2017). Social acceptance of bioenergy in the context of climate change and sustainability - A review. Curr. Opin. Green Sustainable Chem., 8: 5-9 **(5 pages).**

Gabisa, E.W.; Gheewala, S.H., (2019). Potential, environmental, and socio-economic assessment of biogas production in Ethiopia: The case of Amhara regional state. Biomass Bioenergy, 122: 446-456 **(11 pages)**.

Gareiou, Z.; Drimili, E.; Zervas, E., (2021). 12 - Public acceptance of renewable energy sources. In G. L. Kyriakopoulos (Ed.), Low Carbon Energy Technol. Sustainable Energy Syst., Academic Press, 309-327 **(19 pages).**

Gosling, D., (1982). Biogas for Thailand's rural development: Transferring the technology. Biomass, 2(4): 309-316 **(18 pages)**.

Haidt, J., (2001). The emotional dog and its rational tail: A social

intuitionist approach to moral judgment. Psychol. Rev., 108(4): 814–834 **(21 pages).**
Han, J.; Mol, A.P.J.; Lu, Y.; Zhang, L., (2008). Small-scale bioenergy projects in rural China: Lessons to be learnt. Energy Policy. 36(6): 2154-2162 **(9 pages)**.
Haseeb, M., (2019). Analysis of biogas technology adoption at household level and its impact on sustainable livelihoods. Int. J. Eng. Works. 6(9): 314-323 **(10 pages).**
Hernik, J.; Noszczyk, T.; Rutkowska, A., (2019). Towards a better understanding of the variables that influence renewable energy sources in eastern Poland. J. Cleaner Prod., 241: 118075 **(10 pages)**.
IEA, (2020). Outlook for biogas and biomethane: Prospects for organic growth, IEA, Paris **(93 pages).**
IEA, (2023). Renewables 2023, IEA, Paris **(143 pages).**
IEA, (2024). Renewables 2024, IEA, Paris **(177 pages).**
IEA Bioenergy, (2017). Methane emissions from biogas plants, Methods for measurement, results and effect on greenhouse gas balance of electricity produced. Task. 37: 2017: 12 **(52 pages).**
IESR (2019). Indonesia clean energy outlook tracking progress and review of clean energy development in Indonesia. Jakarta: Institute for Essential Services Reform **(72 pages).**
IPCC, (2021). AR6 Climate Change 2021: The Physical Science Basis. Cambridge University Press **(16 pages).**
Jabeen, G.; Yan, Q.; Ahmad, M.; Fatima, N.; Jabeen, M.; Li, H.; Qamar, S., (2020). Household-based critical influence factors of biogas generation technology utilization: A case of Punjab province of Pakistan. Renewable Energy, 154: 650-660 **(11 pages).**
Jameel, M.K.; Mustafa M.A.; Ahmed H.S.; Mohammed Aj.; Ghazy H.; Shakir M.N.; Lawas, A.M.; Mohammed, S.k.; Idan, A.H.; Mahmoud, Z.H.; Sayadi, H.; Kianfar, E., (2024). Biogas: Production, properties, applications, economic and challenges: A review. Results Chem., 7: 101549 **(30 pages).**
K House, H.; DeBruyn, J.; Jack, R., (2007). A survey of biogas production systems in Europe, and their application to North American Dairies. Sixth International Dairy Housing Conference Proceeding, 16-18 June 2007, (Minneapolis, Minnesota) St. Joseph, MI **(24 pages)**.
Kaldellis, J.K., (2005). Social attitude towards wind energy applications in Greece. Energy Policy, 33: 595-602 **(8 pages)**.
Kasperson, R.E.; Ram, B.J., (2013). The public acceptance of new energy technologies. Daedalus. 142(1): 90–96 **(7 pages)**.
Kortsch, T.; Hildebrand, J.; Schweizer-Ries, P., (2015). Acceptance of biomass plants - Results of a longitudinal study in the bioenergy-region Altmark. Renewable Energy, 83: 690-697 **(8 pages).**
Kromus, S.; Wachter, B.; Koschuh, W.; Mandl, M.; Krotscheck, C.; Narodoslwsky, M., (2004). The green biorefinery Austria – development of an integrated system for green biomass utilization. Chem. Biochem. Eng. Q., 18(1):7–12 **(6 pages)**.
Kulla, M.; Novotny, L.; Pregi, L., (2022). The role and perception of biogas in the energy transformation in Slovakia. Geographia Cassoviensis, 16(1): 52-75 **(14 pages).**
Lantz, M.; Svensson, M.; Björnsson, L.; Börjesson, P., (2007). The prospects for an expansion of biogas systems in Sweden-Incentives, barriers and potentials. Energy Policy. 35(3):1830-1843 **(13 pages).**
Luo, T.; Shen, B.; Mei, Z.; Hove, A.; Ju, K., (2024). Unlocking the potential of biogas systems for energy production and climate solutions in rural communities. Nat. Commun., 15(1): 5900 **(10 pages)**.
Mancini E.; Raggi A., (2022). Out of sight, out of mind? The importance of local context and trust in understanding the social acceptance of biogas projects: A global scale review. Energy Res. Social Sci., 91: 102697 **(13 pages)**.
Maphosa, M.; Maphosa, V., (2022). A bibliometric analysis of the effects of electronic waste on the environment. Global J. Environ. Sci. Manage. 8(4): 589-606 **(18 pages)**.
McCormick, K., (2010). Communicating bioenergy: A growing challenge. Biofuels, Bioprod. Biorefin., 4(5): 494-502 **(9 pages)**.
Meidiana, C.; Hidayah, A.; Wijayanti, W.P., (2020). Factors influencing the biogas acceptance in rural area. IOP Conference Series: Earth and Environ. Sci., 520(1): 012006 **(6 pages)**.
Mercer-Mapstone, L.; Rifkin, W.; Louis, W.R.; Moffat, K., (2018). Company-community dialogue builds relationships, fairness, and trust leading to social acceptance of Australian mining developments. J. Cleaner Prod., 184: 671-677 **(16 pages)**.
Miltner, M.; Makaruk, A.; Harasek, M., (2017). Review on available biogas upgrading technologies and innovations towards advanced solutions. J. Cleaner Prod. 161: 1329–1337 **(9 pages).**
Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G., (2009). The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. J. Clin. Epidemiol., 62: 1006–1012 **(7 pages)**.
Moula, M.E.; Maula, J.; Hamdy, M.; Fang, T.; Jung, N.; Lahdelma, R., (2013). Researching social acceptability of renewable energy technologies in Finland. Int. J. Sustainable Built Environ., 2(1):89-98 **(10 pages)**.
Mukeshimana, M.C.; Zhao, Z.-Y.; Ahmad, M.; Irfan, M., (2021). Analysis on barriers to biogas dissemination in Rwanda: AHP approach. Ren. Energy. 163: 1127-1137 **(11 pages).**
Mühl, D.D.; de Oliveira, L., (2022). Features of anaerobic digestion plants in the brazilian agricultural sector. Cleaner Circ. Bioecon., 1: 100001 **(9 pages).**
Nadaï, A., (2007). Planning, siting and the local acceptance of wind power: Some Lessons from the French case. Energy Policy. 35(5): 2715-2726 **(11 pages).**
Nathalie Bachmann, E.S.A., (2013). 8 - Design and engineering of biogas plants. In A. Wellinger, J.; Murphy, D.; Baxter (Eds.), The Biogas Handbook. Woodhead Publishing, 191-211 **(20 pages).**
Ni, J.-Q.; Nyns, E.-J., (1996). New concept for the evaluation of rural biogas management in developing countries. Energy Convers. Manage., 37(10):1525-1534 **(10 pages)**.
Nielsen, M.B., (2022). Identifying challenges and drivers for deployment of centralized biogas plants in Denmark. Sustainability. 14(13): 8021 **(28 pages)**.
Nielsen, M.B.; Lybæk, R.; Kjær, T., (2022). Successfully navigating the project lifecycle for deployment of centralized biogas projects - the case of Solrod biogas. Energies. 15(16): 5879 **(21 pages).**
Nisbet, E.G.; Fisher, R.E.; Lowry, D.; France, J.L.; Allen, G.; Bakkaloglu, S.; Broderick, T.J.; Cain, M.; Coleman, M.; Fernandez, J.; Forster, G.; Griffiths, P.T.; Iverach, C.P.; Kelly, B.F.J.; Manning, M.R.; Nisbet-Jones, P.B.R.; Pyle, J.A.; Townsend-Small, A.; al-Shalaan, A.; Warwick, N.; Zazzeri, G., (2020). Methane mitigation: methods to reduce emissions, on the path to the Paris Agreement. Rev. Geophys., 58: e2019RG000675 **(51 pages).**
Nsair, A.; Onen Cinar, S.; Alassali, A.; Abu Qdais, H.; Kuchta, K., (2020). Operational parameters of biogas plants: a review and evaluation study. Energies. 13(15): 3761 **(27 pages).**
Oliveira, H.R.; Kozlowsky-Suzuki, B.; Björn, A.; Shakeri Yekta, S.; Caetano, C.F.; Pinheiro, É.F.M.; Marotta, H.; Bassin, J.P.; Oliveira, L.; Reis, M.D.M.; Schultz, M.S.; Mangiavacchi, N.; Ferreira-Leitão, V.S.; Fasheun, D.O.; Silva, F.G.; Taveira, I.; Alves, I.R.D.F.S.; Castro, J.; Durão, J.V.; Guimarães, J.; Rocha, M.E.; Tomasini, M.; Martins, P.V.D.O.; Presciliano, R.; Santos, S.B.D.; Faria, T.M.; Corrêa, T.;

Linde, T.D.N.M.P.D.; Abreu, F.; Enrich-Prast, A., (2024). Biogas potential of biowaste: A case study in the state of Rio de Janeiro, Brazil. Renewable Energy. 221: 119751 **(11 pages).**

Obaideen, K.; Abdelkareem, M.A.; Wilberforce, T.; Elsaid, K.; Sayed, E.T.; Maghrabie, H.M.; Olabi, A.G., (2022). Biogas role in achievement of the sustainable development goals: Evaluation, Challenges, and Guidelines. J. Taiwan Inst. Chem. Eng., 131: 104207 **(20 pages).**

Ortiz, W.; Terrapon-Pfaff, J.; Dienst, C., (2017). Understanding the diffusion of domestic biogas technologies. Systematic conceptualization of existing evidence from developing and emerging countries. Renewable Sustainable Energy Rev., 74: 1287-1299 (13 **pages).**

Osei-Marfo, M.; Awuah, E.; de Vries, N.K., (2018). Biogas technology diffusion and shortfalls in the central and greater Accra regions of Ghana. Water Pract. Technol., 13(4): 932-946 **(15 pages).**

Page, M.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D., et al., (2021). PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. BMJ, 372: n160 **(36 pages)**.

Paolini, V.; Petracchini, F.; Segreto, M.; Tomassetti, L.; Naja, N.; Cecinato, A. (2018). Environmental impact of biogas: A short review of current knowledge. J. Environ. Sci. Health., Part A, 53(10): 899–906 **(8 pages)**.

Parikh, J.K.; Parikh, K.S., (1977). Mobilization and impacts of bio-gas technologies. Energy. 2(4):441-455 **(14 pages)**.

Patinvoh, R.J.; Taherzadeh, M.J., (2019). Challenges of biogas implementation in developing countries. Curr. Opin. Environ. Sci. Health. 12: 30-37 **(7 pages).**

Perlaviciute, G.; Steg, L., (2015). The influence of values on evaluations of energy alternatives. Renew. Energy. 77: 259–267 **(9 pages).**

Perlaviciute, G.; Steg, L.; Contzen, N.; Roeser, S.; Huijts, N., (2018). Emotional responses to energy projects: insights for responsible decision making in a sustainable energy transition. Sustainability. 10: 2526 **(12 pages)**.

Plieninger, T.; Bens, O.; Hüttl, R.F., (2006). Perspectives of bioenergy for agriculture and rural areas. Outlook Agric., 35(2):123-127 **(14 pages)**.

Pollesch, N.L.; Dale, V.H., (2016). Normalization in sustainability assessment: Methods and implications. Ecol. Econ., 130: 195-208 **(14 pages).**

Rahman, M.M.; Hasan, M.M.; Paatero, J.V.; Lahdelma, R., (2014). Hybrid application of biogas and solar resources to fulfill household energy needs: A potentially viable option in rural areas of developing countries. Ren. Energy. 68: 35-45 **(11 pages).**

Razinkov, M.I.; Zhukova, A.A.; Jovanovich, S.; Sorokin, D.E.; Saidmurodova, M.A.; Abramov, V.L.; Novikova, O.V.; Afanasyev, Valentin Ya, (2021). Assessment and prospects of biogas use. IOP Conference Series: Earth Env. Sci., 723(5): 052041 **(7 pages)**.

Roberts, R.C., (2001). Emotions: An essay in aid of moral psychology. Cambridge University Press: Cambridge, UK, 2003 **(352 pages).**

Rocha-Meneses, L.; Luna-delRisco, M.; González, C.A.; Moncada, S.V.; Moreno, A.; Sierra-Del Rio, J.; Castillo-Meza, L.E., (2023). An Overview of the Socio-Economic, Technological, and Environmental Opportunities and Challenges for Renewable Energy Generation from Residual Biomass: A Case Study of Biogas Production in Colombia. Energies. 16: 5901 **(20 pages).**

Roeser, S., (2011). Moral emotions and intuitions. Palgrave Macmillan: Basingstoke, UK, 2011 **(206 pages).**

Sarker, S.; Wang, S.; Adnan, K.M.; Sattar, M., (2020). Economic feasibility and determinants of biogas technology adoption: Evidence from Bangladesh. Ren. Sustainable Energy Rev., 123: 109766 **(12 pages).**

Scarlat, N.; Dallemand, J.-F.; Monforti-Ferrario, F.; Banja, M.; Motola, V., (2015). Renewable energy policy framework and bioenergy contribution in the European Union – An overview from National Renewable Energy Action Plans and Progress Reports. Renewable Sustainable Energy Rev., 51:969-985 **(17 pages).**

Scheutz, C.; Fredenslund, A.M., (2019). Total methane emission rates and losses from 23 biogas plants. Waste Manage., 97: 38-46 **(9 pages)**

Schumacher, K.; Schultmann, F., (2017). Local acceptance of biogas plants: a comparative study in the trinational upper Rhine region. Waste Biomass Valorization. 8: 2393–2412 **(20 pages).**

Segreto, M.; Principe, L.; Desormeaux, A.; Torre, M.; Tomassetti, L.; Tratzi, P.; Paolini, V.; Petracchini, F., (2020). Trends in social acceptance of renewable energy across Europe—A literature review. Int. J. Environ. Res. Public Health, 17(24): 9161 **(19 pages)**.

Segreto, M.; Torre, M.; Tratzi, P.; Tomassetti, L.; Paolini, V.; Borin, D.; Petracchini, F., (2019). Social acceptance of bioenergy in Europe. European Biomass Conference Exhibition Proceeding. 1563-1564 **(2 pages).**

Sharpton, T.; Lawrence, T.; Hall, M., (2020). Drivers and barriers to public acceptance of future energy sources and grid expansion in the United States. Renewable Sustainable Energy Rev., 126: 109826 **(12 pages)**.

Sims, R.E.H., (2003). Bioenergy to mitigate for climate change and meet the needs of society, the economy and the environment. Mitigation Adapt. Strategies Global Change. 8(4): 349–370 **(21 pages).**

Situmeang, R.; Mazancová, J.; Roubík, H., (2022). Technological, economic, social and environmental barriers to adoption of small-scale biogas plants: case of Indonesia. Energies. 15(14): 5105 **(16 pages).**

Soland, M.; Steimer, N.; Walter, G., (2013). Local acceptance of existing biogas plants in Switzerland. Energy Policy, 61(C): 802-810 **(9 pages)**.

Soleas, E., (2021). Environmental factors impacting the motivation to innovate: a systematic review. J. Innovation Entrepreneurship. 10: 17 **(18 pages).**

Sumiyati, S.; Samadikun, B.P.; Widiyanti, A.; Budihardjo, M.A.; Al Qadar, S.; Puspita, A.S., (2024). Life cycle assessment of agricultural waste recycling for sustainable environmental impact. Global J. Environ. Sci. Manage. 10(2): 907-938 **(32 pages)**.

Surendra, K.C.; Takara, D.; Hashimoto, A.G.; Khanal, S.K., (2014). Biogas as a sustainable energy source for developing countries: Opportunities and challenges. Renewable Sustainable Energy Rev., 31: 846-859 **(14 pages)**.

Terwel, B.; Harinck, F.; Ellemers, N.; Daamen, D., (2011). Going beyond the properties of CO2 capture and storage (CCS) technology: How trust in stakeholders affects public acceptance of CCS. Int. J. Greenhouse Gas Control, 5(2):181–188 **(8 pages)**.

Thanh Truc, N.; Tran, N.; Nguyen Vo Chau, N.; Bentzen, J., (2017). Factors influencing the adoption of small-scale biogas digesters in developing countries – empirical evidence from Vietnam. Int. Business Res., 10(2): 1-8 **(8 pages)**.

Timonen, K.; Reinikainen, A.; Kurppa, S.; Riipi, I., (2021). Key indicators and social acceptance for bioenergy production potential as part of the green economy transition process in local areas of Lapland. Int. J. Environ. Res. Public Health. 18(2): 527 **(20 pages)**.

Torres-Ceron D.A.; Amaya-Roncancio S.; Fuentes-Gandara F.; Restrepo-Parra E.; Bohorquez-Santiago L.; Velasquez-Tamayo J.P., (2025). Scientometric analysis of computational calculations

on hydrogen adsorption. Global J. Environ. Sci. Manage., 11(1): 295-320 **(26 pages).**

Twyhues, P.T., (2020) Become aware and take care - social acceptance of bioenergy in the Netherlands and Germany: A comparison between two countries on the basis of differing energy policies. Essay: 81647 **(55 pages)**.

Upham, P.; Oltra, C.; Boso, À., (2015). Towards a cross-paradigmatic framework of the social acceptance of energy systems. Energy Res. Soc. Sci., 8: 100–112 **(13 pages)**.

van der Horst, D., (2007). NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. Energy Policy, 35(5): 2705–2714 **(10 pages)**.

van Dijk, M.; Goedegebure, R.; Nap, J.-P., (2024). Public acceptance of biomass for bioenergy: The need for feedstock differentiation and communicating a waste utilization frame. Renewable Sustainable Energy Rev., 202: 114670 **(12 pages)**.

van Eck N.J.; Waltman, L., (2018). VOSviewer Manual. Manual for VOSviewer (Version 1.6.8) **(54 pages).**

Velásquez Piñas, J.A.; Venturini, O.J.; Silva Lora, E.E.; del Olmo, O.A.; Calle Roalcaba, O.D., (2019). An economic holistic feasibility assessment of centralized and decentralized biogas plants with mono-digestion and co-digestion systems. Renewable Energy, 139: 40-51 **(12 pages)**.

Venko, B., (2022). Biogas production: evaluation and possible applications. In A. Abd El-Fatah; S. El-Sayed (Eds.), Biogas. IntechOpen **(18 pages)**.

Walekhwa, P.N.; Mugisha, J.; Drake, L., (2009). Biogas energy from family-sized digesters in Uganda: Critical factors and policy implications. Energy Policy. 37(7):2754-2762 **(9 pages)**.

Wexler, M.N., (1996). A sociological framing of the NIMBY (not-in-my-backyard) syndrome. Int. Rev. Modern Soc., 26(1): 91–110 **(10 pages)**.

Wu, J.; Atchike, D.W.; Ahmad, M., (2023). Crucial adoption factors of renewable energy technology: Seeking green future by promoting biomethane. Processes. 11: 2005 **(17 pages)**.

Wüstenhagen, R.; Wolsink, M.; Bürer, M.J., (2007). Social acceptance of renewable energy innovation: An introduction to the concept. Energy Policy. 35(5): 2683-2691 **(9 pages).**

Zabaniotou, A., (2018). Redesigning a bioenergy sector in EU in the transition to circular waste-based Bioeconomy-A multidisciplinary review. J. Cleaner Prod., 177: 197–206 **(10 pages).**

Xue, S.; Song, J.; Wang, X.; Shang, Z.; Sheng, C.; Li, C.; Zhu, Y.; Liu, J., (2020). A systematic comparison of biogas development and related policies between China and Europe and corresponding insights. Renewable Sustainable Energy Rev., 117(C): 109474 **(14 pages).**

AUTHOR (S) BIOSKETCHES

Biró, K., Ph.D., Postdoctoral Researcher, ASEAN Institute for Health Development, Mahidol University, Nakhon Pathom 73170, Thailand.
- Email: *kinga.bir@mahidol.ac.th*
- ORCID: 0000-0002-9406-9038
- Web of Science ResearcherID: AAS-8171-2020
- Scopus Author ID: 57202094790
- Homepage: https://aihd.mahidol.ac.th/main/AIHD_EN/Staff_Academic_Instructor.php

Woon, K.S., Ph.D., Associate Professor, [1]School of Energy and Chemical Engineering, Xiamen University Malaysia, Malaysia. [2]*Carbon Neutrality and Climate Change Thrust, Hong Kong University of Science and Technology, Guangzhou, China.*
- Email: *koksin.woon@xmu.edu.my*
- ORCID: 0000-0003-0149-6661
- Web of Science ResearcherID: V-3614-2019
- Scopus Author ID: 55985523600
- Homepage: https://sece.xmu.edu.my/faculty/academic-staff/vincent-woon-kok-sin

Ounsaneha, W., Ph.D., Assistant Professor, Faculty of Science and Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage, Klong Nuang, Klong Luang, Pathumthani 13180, Thailand.
- Email: *weerawat@vru.ac.th*
- ORCID: 0009-0000-7297-3803
- Web of Science ResearcherID: NA
- Scopus Author ID: 37117631800
- Homepage: https://sci.vru.ac.th/home/personnel/62

Rattanapan, C., Ph.D., Associate Professor, ASEAN Institute for Health Development, Mahidol University, Nakhon Pathom 73170, Thailand.
- Email: *cheerawit.rat@mahidol.edu*
- ORCID: 0000-0002-1799-422X
- Web of Science ResearcherID: NA
- Scopus Author ID: 24460571700
- Homepage: https://aihd.mahidol.ac.th/main/AIHD_EN/Lect_cheerawit.php

HOW TO CITE THIS ARTICLE

Biró, K.; Woon, K.S.; Ounsaneha, W.; Rattanapan, C., (2025). A global perspective on sustainable pathways for biogas adoption. Global J. Environ. Sci. Manage., 11(2): 825-856.

DOI: 10.22034/gjesm.2025.02.25

URL: https://www.gjesm.net/article_720100.html

PUBLICATION ETHICS

The ethical policy of GJESM is based on the Committee on Publication Ethics (COPE) guidelines and complies with International Committee of GJESM Editorial Board codes of conduct. Readers, authors, reviewers and editors should follow these ethical policies once working with GJESM. The ethical policy of GJESM is liable to determine which of the typical research papers or articles submitted to the journal should be published in the concerned issue. For information on this matter in publishing and ethical guidelines please visit http://publicationethics.org

Duties and Responsibilities of Publishers

1. GJESM is committing to ensure that editorial decisions on manuscript submissions are the final.
2. GJESM is promising to ensure that the decision on manuscript submissions is only made based on professional judgment and will not be affected by any commercial interests.
3. GJESM is committing to maintain the integrity of academic and research records.
4. GJESM is monitoring the ethics by Editor-in-Chief, Associate Editors, Editorial Board Members, Reviewers, Authors, and Readers.
5. GJESM is always checking the plagiarism and fraudulent data issues involving in the submitted manuscript.
6. GJESM is always willing to publish corrections, clarifications and retractions involving its publications as and when needed.

Duties and Responsibilities of Editors

1. The Editors of the journal should have the full authority to reject/accept a manuscript.
2. The Editors of the journal should maintain the confidentiality of submitted manuscripts under review or until they are published.
3. The Editor-in-Chief should take a decision on submitted manuscripts, whether to be published or not with other editors and reviewers
4. The Editors of the journal should preserve the anonymity of reviewers.
5. The Editors of the journal should disclose and try to avoid any conflict of interest.
6. The Editors of the journal should maintain academic integrity and strive to meet the needs of readers and authors.
7. The Editors of the journal should be willing to investigate plagiarism and fraudulent data issues and willing to publish corrections, clarifications, retractions, and apologies when needed.
8. The Editors of the journal should have the limit themselves only to the intellectual content.
9. The Editors of the journal must not disclose any information about submitted manuscripts to anyone other than the corresponding author, reviewers, potential reviewers, other editorial advisers, and the publisher, as appropriate.
10. Unpublished materials disclosed in a submitted paper will not be used by the editor or the members of the editorial board for their own research purposes without the author's explicit written consent.

Duties and Responsibilities of Reviewers

1. The Reviewers of the journal should assist the Editors in taking the decision for publishing the submitted manuscripts.
2. The Reviewers should maintain the confidentiality of manuscripts, which they are invited to review.
3. The Reviewers should provide comments in time that will help editors to make decision on the submitted manuscript to be published or not.
4. The Reviewers are bound to treat the manuscript received for peer reviewing as confidential, and must not use the information obtained through peer review for personal advantage.
5. The Reviewers comments against each invited manuscript should be technical, professional and objective.
6. The Reviewers should not review the manuscripts in which they have found conflicts of interest with any of the authors, companies, or institutions.
7. The Reviewers should disclose and try to avoid any conflict of interest.

Duties and Responsibilities of Authors

1. Manuscripts must be submitted only in English and should be written according to sound grammar and proper terminology.
2. Manuscripts must be submitted with the understanding that they have not been published elsewhere (except in the form of an abstract or as part of a published lecture, review, or thesis) and are not currently under consideration by another journal published by or any other publisher.
3. The submitting (corresponding) author is responsible for ensuring that the manuscript article's publication has been approved by all the other coauthors.
4. In order to sustain the peer review system, authors have an obligation to participate in peer review process to evaluate manuscripts from others.
5. It is also the authors' responsibility to ensure that the manuscripts emanating from a particular institution are submitted with the approval of the necessary institution.
6. It is a condition for submission of a manuscript that the authors permit editing of the paper for readability.
7. Authors are requested to clearly identify who provided financial support for the conduct of research and/or preparation of the manuscript and briefly describe the role of the funder/sponsor in any part of the work.
8. A copy right release and conflict of interest disclosure form must be signed by the corresponding author in case of multiple authorships, prior to the acceptation of the

manuscript, by all authors, for publication to be legally responsible towards the Journal ethics and privacy policy.

9. Under open access license, authors retain ownership of the copyright for their content, but allow anyone to download, reuse, reprint, modify, distribute, and/ or copy the content as long as the original authors and source are cited properly.
10. All authors have agreed to allow the corresponding author to serve as the primary correspondent with the editorial office, to review the edited manuscript and proof.
11. When author(s) discovers a significant error or inaccuracy in his/her own published work, it is the author's obligation to promptly notify the journal editor or publisher to retract or correct the manuscript.
12. All authors must know that that the submitted manuscripts under review or published with GJESM are subject to screening using Plagiarism Prevention Software. Plagiarism is a serious violation of publication ethics.

Violation of Publication Ethics

1. **Plagiarism:** Plagiarism is intentionally using someone else's ideas or other original material as if they are one's own. Copying even one sentence from someone else's manuscript, or even one of your own that has previously been published, without proper citation is considered by GJESM Journals as plagiarism. All manuscripts under review or published with GJESM are subject to screening using plagiarism prevention software. Thus, plagiarism is a serious violation of publication ethics. The development of CrossCheck is a service that helps editors to verify the originality of papers. CrossCheck is powered by the Ithenticate software from iParadigms, known in the academic community as providers of Turnitin. For a searchable list of all journals in the CrossCheck database, please visit: www.ithenticate.com/search
2. **Data Fabrication and Falsification:** Data fabrication and falsification means the researcher did not really carry out the study, but made up data or results and had recorded or reported the fabricated information. Data falsification means the researcher did the experiment, but manipulated, changed, or omitted data or results from the research findings.
3. **Simultaneous Submission:** Simultaneous submission occurs when a manuscript (or substantial sections from a manuscript) is submitted to a journal when it is already under consideration by another journal.
4. **Duplicate Publication:** Duplicate publication occurs when two or more papers, without full cross referencing, share essentially the same hypotheses, data, discussion points, and conclusions.
5. **Redundant Publications:** Redundant publications involve the inappropriate division of study outcomes into several articles, most often consequent to the desire to plump academic vitae.
6. **Improper Author Contribution or Attribution:** All listed authors must have made a significant scientific contribution to the research in the manuscript and approved all its claims. Don't forget to list everyone who made a significant scientific contribution, including students and laboratory technicians.
7. **Citation Manipulation:** Citation Manipulation is including excessive citations, in the submitted manuscript, that do not contribute to the scholarly content of the article and have been included solely for the purpose of increasing citations to a given author's work, or to articles published in a particular journal. This leads to misrepresenting the importance of the specific work and journal in which it appears and is thus a form of scientific misconduct.

Handling Cases of Misconduct

Once GJESM confirms a violation against GJESM's publication ethics, GJESM addresses ethical concerns diligently following an issue-specific standard practice as summarized below.

1. The first action of the journal Editor is to inform the Editorial Office of GJESM by supplying copies of the relevant material and a draft letter to the corresponding author asking for an explanation in a nonjudgmental manner.
2. If the author's explanation is unacceptable and it seems that serious unethical conduct has taken place, the matter is referred to the Publication Committee via Editorial Office. After deliberation, the Committee will decide whether the case is sufficiently serious to warrant a ban on future submissions.
3. If the infraction is less severe, the Editor, upon the advice of the Publication Committee, sends the author a letter of reprimand and reminds the author of GJESM publication policies; if the manuscript has been published, the Editor may request the author to publish an apology in the journal to correct the record.
4. Notification will be sent to corresponding author and any work by the author responsible for the violation or any work these persons coauthored that is under review by GJESM journal will be rejected immediately.
5. The authors are prohibited from serving on GJESM editorial board and serving as a reviewer for GJESM Journal. GJESM reserves the right to take more actions.
6. In extreme cases, notifications will be sent to the affiliations of the authors and the authors are prohibited from submitting their work to GJESM for 5 years.
7. In serious cases of fraud that result in retraction of the article, a retraction notice will be published in the journal and will be linked to the article in the online version. The online version will also be marked "retracted" with the retraction date.

GUIDE FOR AUTHORS

"Global Journal of Environmental Science and Management" (GJESM) is a double blind peer reviewed electronic and print quarterly publication concerned with all aspects of environmental science and management. GJESM publishes original research papers, review papers, case reports and short communications, letters to editor and authors' response about letters to editor across the broad field of environment. These include but are not limited to environmental science, environmental management, environmental engineering, environmental planning and design, urban and regional landscape design and industrial ecology. Environmentalist disciplines are invited to contribute their knowledge and experience. The publication appears at regular intervals time quarterly. The Journal database is fully open access and full text of published articles are available for everyone who can get access to the Journal website free of cost. The authors never pay any charges for submission, article processing and publication.

Guide for Authors: More details on guide for authors refer: http://gjesm.net/journal/authors.note

GENERAL

1. Authors should submit their contributions electronically through the GJESM website submission system to the Editorial Office.

2. Manuscripts must be submitted only in English and should be written according to sound grammar and proper terminology. Manuscripts should be typed in Times New Roman of 11 pt. font and in MS-Word format in one column with 2.5 cm margin at each side. Manuscript submission must be applied once in order to obtain only one submission ID number. More than one submission for a single manuscript can lose the chance of the manuscript consideration. Manuscript must be accompanied by a covering letter including title and author(s) name.

3. There are no strict formatting requirements but all manuscripts must contain the essential elements needed to convey your manuscript, for example Abstract, Keywords, Introduction, Materials and Methods, Results, Conclusions, Artwork and Tables with Captions. Please ensure the figures and the tables included in the single file are placed next to the relevant text in the manuscript, rather than at the bottom or the top of the file. There are no strict requirements on reference formatting at submission. References can be in any style or format as long as the style is consistent.

BEFORE YOU BEGIN

1. Peer-Review Process: In order to sustain the peer review system, authors have an obligation to participate in peer review process to evaluate manuscripts from others. When appropriate, authors are obliged to provide retractions and/or corrections of errors to the editors and the Publisher. All papers submitted to GJESM journal will be peer reviewed for at least one round. GJESM journal adopts a double-blinded review policy: authors are blind to reviewers, but reviewers are not blind to authors. After receiving reviewers' comments, the editorial team member makes a decision. Because reviewers sometimes do not agree with each other, the final decision sent to the author may not exactly reflect recommendations by any of the reviewers. The decision after each round of peer review may include (a) Accept without any further changes, (b) Accept with minor revision, (c) Major changes are necessary for resubmission and (d) Decline without encouraging resubmission.

2. Post-Publication Evaluation: In addition to rapid Peer Review Process, the GJESM Journal has Post-Publication Evaluation by the scientific community. Post-Publication Evaluation is concentrated to ensure that the quality of published research, review and case report meets certain standards and the conclusions that are presented are justified. The post-publication evaluation includes online comments and citations on published papers. Authors may respond to the comments of the scientific community and may revise their manuscript. The Post-Publication Evaluation is described in such a way; it is allowing authors to publish quickly about Environmental science, management, engineering and technology concepts.

3. Publication Ethics: The ethical policy of GJESM is based on the Committee on Publication Ethics (COPE) guidelines and complies with International Committee of GJESM Editorial Board codes of conduct. Readers, authors, reviewers and editors should follow these ethical policies once working with GJESM. The ethical policy of GJESM is liable to determine which of the typical research papers or articles submitted to the journal should be published in the concerned issue. The ethical policy insisted the Editor-in-Chief, may confer with other editors or reviewers in making the decision. Visit at: http://publicationethics.org

4. Conflict of Interest: Authors are requested to evident whether impending conflicts do or do not exist. A copyright transfer agreement is signed by the corresponding author, upon the acceptance of the manuscript, on behalf of all authors, for publication to be legally responsible towards the journal ethics and privacy policy. Authors will be notified as soon as possible of decisions concerning the suitability of their manuscripts for publication in the journal. The submitted materials may be considered for inclusion but cannot be returned and Editors of the journal reserve the right to accept or reject any article in any stage, if necessary. Conflict of Interest Disclosure form can be found at: www.gjesm.org/conflict_of_interest_discloure_form.docx

5. Submission Declaration and Verification: While submitting a manuscript to GJESM, all contributing author(s) must verify that the manuscript represents authentic and valid work and that neither this manuscript nor one with significantly similar content under their authorship has been published or is being considered for publication elsewhere including electronically in the same form, in English or in other language, without the written consent the copy right holder.

6. Authorship: All contributing authors should qualify for authorship and corresponding author should sign the authorship form while submitting the manuscript. It can be found at:
(http://www.gjesm.net/data/gjesm/news/authorship_form.docx).

7. Changes to Authorship: After the manuscript is submitted or accepted for publication, the corresponding author is required to send a request to add or remove an author or to rearrange the author names of the submitted/accepted manuscript by sending the change of authorship form to editorial office. No authorship change is allowed after publication of manuscript. More details may be found at:
(http://www.gjesm.net/data/gjesm/news/change_of_authorship_form.docx)

8. Retained Author Rights: As an author, author or authors' employer or institution retains certain rights. For more information on author rights, found at:
www.gjesm.org/retained_authors_right.docx.

9. Copy Right: Journals should make clear the type of copyright under which authors' work will be published. For open access articles the publisher uses an exclusive licensing agreement in which authors retain copyright in their manuscript. More details may be found at: (www.gjesm.org/copyright_form.docx)

10. User license Agreement: GJESM provides access to archived material through GJESM archives. Manuscripts are the parts of an open archive are made freely available from GJESM website after certain period, which begins from the final publication date of the manuscript. All articles published open access will be immediately and permanently free for everyone to read and download. Permitted reuse is defined by Creative Commons user license called ***Creative Commons Attribution***. Visit at: **(**Creative Commons Attribution 4.0 International (CC BY 4.0)**)**

11. Plagiarism Prevention and Violation of Publication Ethics: All manuscripts under review or published with GJESM are subject to screening using Plagiarism Prevention Software. Plagiarism is a serious violation of publication ethics. Other violations include duplicate publication, data fabrication and falsification, and improper credit of author contribution. Thus, the Plagiarism or Fraudulent or knowingly inaccurate statements constitute unethical behavior are unacceptable and submitting the same manuscript to more than one journal concurrently constitutes unethical publishing behavior and is unacceptable. The development of CrossCheck is a service that helps editors to verify the originality of papers. CrossCheck is powered by the Ithenticate software from iParadigms, known in the academic community as providers of Turnitin. For more details visit at: www.ithenticate.com/search

12. Handling Cases of Misconduct: Once GJESM confirms a violation against GJESM's publication ethics, the following actions will be taken.

a. The work is rejected / retracted immediately. Notification will be sent to corresponding authors. In extreme cases, notifications will be sent to the affiliations of the authors.
b. The authors are prohibited from submitting their work to GJESM for 5 years.
c. Any work by the authors responsible for the violation or any work these persons coauthored that is under review by any GJESM journal will be rejected immediately.
d. The authors are prohibited from serving on GJESM editorial board. GJESM reserves the right to take more actions.

MANUSCRIPT PREPARATION

1. Title Page: The title page should include: the name(s) of the author(s), a concise and informative title, the affiliation(s) and address (es) of the author(s), and e-mail address, telephone and fax numbers of the corresponding author.

2. Manuscript Title: Title of up to 17 words should not contain the name of locations, countries or cities of the research as well as abbreviations. The title should be oriented to Environmental issues while not being obscure or meaningless.

3. Abstract: An abstract of 150 to 250 words that sketches the purpose of the study; basic procedures; main findings its novelty; discussions and the principal conclusions, should not contain any undefined abbreviations or references.

4. Keywords: Provide 5 to 7 keywords which can be used for indexing purposes. Keywords should not repeat the words of the manuscript title or contain abbreviations and shall be written in alphabetical order as separated by semicolon.

5. Introduction: The Introduction should state the purpose of the investigation and identify clearly the gap of knowledge that will be filled in the Literature review study. Date and location of the research carried out throughout the study must be mentioned at the end of this section.

6. Materials and methods: The Materials and Methods section should provide enough information to permit repetition of the experimental work. It should include clear descriptions and explanations of sampling procedures, experimental design, and essential sample characteristics and descriptive statistics, hypothesis tested, exact references to literature describing the tests used in the manuscript, number of data involved in statistical tests, etc.

7. Results and Discussion: The Results section should describe the outcome of the study. Data should be presented as concisely as possible - if appropriate in the form of tables or figures, although very large tables should be avoided. The Discussion should be an interpretation of the results and their significance with reference to work by other authors. Please note that the policy of the Journal with respect to units and symbols is that of SI symbols.

8. Tables: Do not submit tables and graphs as photograph. Place explanatory matters in footnotes, not in the heading. Do not use internal horizontal and vertical rules. Tables should be called out in the text and should have a clear and rational structure and consecutive numerical order. All tables should be numbered 1, 2, 3, etc. Give enough information in subtitles so that each table is understandable without reference to the text. Footnotes to tables should be indicated by superscript lower-case letters (or asterisks for significance values and other statistical data) and included beneath the table body.

9. Figures: Figures/ illustrations should be in high quality art work, within 200-300 dpi and separately provided in Excel format. Ensure that figures are clear, labeled, and of a size that can be reproduced legibly in the journal. Each figure should have a concise caption describing accurately what the figure depicts. Figure captions begin with the term Fig. Figures should be with the captions placed below in limited numbers. No punctuation is to be placed at the end of the caption.

10. Conclusion: This section should highlight the major, firm discoveries, and state what the added value of the main finding is, without literature references.

11. Acknowledgements: Acknowledgments of people, grants, funds, etc. should be placed in a separate section before the reference list. The names of funding organizations should be written in full. Financial support affiliation of the study, if exists, must be mentioned in this section. Thereby, the Grant number of financial support must be included.

12. References: All the references should be cited throughout the manuscript text as well as in the Reference section organized in accordance with Harvard system. Groups of references should be listed first alphabetically, then chronologically. The number of references extracted from each journal should not exceed 3 to 5 citations, which is the average acceptable amount. The number of references should not be less than 30 for original paper, less than 100 for review paper. It is substantially recommended to the authors to refer to more recent references rather than old and out of date ones. Volume, issue and pages of the whole references must be specified according to the GJESM format.

Citing and listing of Web references: As a minimum, the full URL should be given. Any further information, if known (Author names, dates, reference to a source publication, etc.), should also be given.

Text: All citations in the text should refer to: 1. Single author: the author's name (without initials, unless there is ambiguity) and the year of publication; 2. Two authors: both authors' names and the year of publication; and 3. Three or more authors: first author's name followed by "et al." and the year of publication. Citations may be made directly (or parenthetically). Groups of references should be listed first alphabetically, then chronologically. Examples: "as demonstrated (Allan, 1996a, 1996b, 1999; Allan and Jones, 1995). Kramer *et al.,* (2000) have recently shown …".

List: References should be arranged first alphabetically and then further sorted chronologically if necessary. More than one reference from the same Author(s) in the same year must be identified by the letters "a", "b", "c", etc., placed after the year of publication.

Journal article: Nouri J.; Lorestani B.; Yousefi N.; Khorasani N.; Hassani A. H.; Seif, F.; Cheraghi M., (2011). Phytoremediation potential of native plants grown in the vicinity of Ahangaran lead-zinc mine. Environ. Earth Sci., 62(3): 639-644.

Book: Davis, M. L., (2005). Introduction to Environmental Engineering, 3rd. Ed. McGraw Hill Inc.

Book chapter: Mettam, G. R.; Adams, L. B., (1999). How to prepare an electronic version of your article, in: Jones, B. S., Smith, R. Z. (Eds.), Introduction to the electronic age. E-Publishing Inc., New York.

Conference paper: Brown, J., (2005). Evaluating surveys of transparent governance. In UNDESA, 6th. Global forum on reinventing government: towards participatory and transparent governance. Seoul, Republic of Korea 24-27 May. United Nations: New York.

Dissertation: Trent, J. W., (1975). Experimental acute renal failure. Ph.D. Dissertation, University of California. USA.

Online document: Cartwright, J., (2007). Big stars have weather too. IOP Publishing Physics Web.
http://physicsworld.com/cws/article/news/2007/jun/26/big-stars-have-weather-too

AFTER ACCEPTANCE

1. Online Proof Correction: Corresponding authors will receive an e-mail with a link to our online proofing system, allowing annotation and correction of proofs online. Use this proof only for checking the typesetting, editing, completeness and correctness of the text, tables and figures. Significant changes to the article as accepted for publication will only be considered at this stage with permission from the Editor-in-Chief. It is important to ensure that all corrections are sent back to us in one communication. Please check carefully before replying, as inclusion of any subsequent corrections cannot be guaranteed. Proofreading is solely the corresponding author responsibility.

2. Offprints: The offprints can be downloading from the GJESM website once the final corrected manuscripts are disseminated.

AUTHORS INQUIRIES

Authors can track their submitted article through GJESM website on author's login section at: http://gjesm.net/contacts?_action=login

Global Journal of Environmental Science and Management (GJESM)

Copyright Transfer Agreement

1. Parties of the agreement

Author (s):

Manuscript Title:

Manuscript ID:

(Herewith referred to as the "materials"),

Journal Title: Global Journal of Environmental Science and Management (GJESM)

2. Subject of the agreement

A) Copyright
1- The Author and each co-authors shall transfer and sell to the Publisher for the length of the copyright starting from the moment the present agreement comes into force the exclusive rights to the materials, including the rights to translate, reproduce, transfer, distribute or otherwise use the materials or parts (fragments) contained therein, for publication in scientific, academic, technical or professional journals or other periodicals and in derivative works thereof, worldwide, in English, in print or in electronic editions of such journals, periodicals and derivative works in all media or formats now existing or that may exist in future, as well as the right to license (or give permission to) third parties to use the materials for publication in such journals, periodicals and derivative works worldwide. The transfer under this agreement includes the right to adapt the presentation of the materials for use in conjunction with computer systems and programs, reproduction or publication in machine-readable format and incorporation into retrieval systems.
2- Reproduction, placement, transfer or any other distribution or use of the materials, or any parts of the materials contained therein, in any way permitted under this Agreement, shall be accompanied by reference to the Journal and mentioning of the Publisher, namely: the title of the article, the name of the Author (Co-authors), the name of the Journal, volume/number, copyright of the publisher.

B) Reserved Rights
The Author (Co-authors) or the employer of the Author (Co-authors) of the materials shall retain all proprietary rights (with the exception of the rights transferred to the Publisher under the present Agreement).

C) Author Guarantee
The Author (Co-authors) guarantees that the materials are an original work, submitted only to GJESM, and have not been published previously.
In case the materials were written jointly with co-authors, the Author guarantees that he/she has informed them of the terms of this Agreement and obtained their signatures or written permission to singe on their behalf.
The Author guarantees as well that:
The materials do not contain libelous statements.
The materials do not infringe on other persons' rights (including without limitation copyrights, patent rights and the trademark right).
The materials do not contain facts or instructions that can cause damage or injury to third parties and their publication does not cause the disclosure of any secret or confidential information

---

Author (Corresponding Author):

Correspondence Address:

Phone:

Fax:

Email:

Corresponding Author Name: Signature Date

On Behalf of the Publisher:

Iran Solid Waste Association,
Faculty of Environment, University of Tehran,
Postal Code: 1417854511, Tehran,
Iran

Telefax: (+9821) 2610 5110

Email: *editor@gjesm.net*

Gjesm.publication@gmail.com

Website: www.gjesm.net

Accepted for publication ☑ Signature Date

PLEASE NOTE: The accepted manuscript cannot be processed for publication until the publisher has received this signed form. The form MUST be signed by the Corresponding Author and then scanned and sent through the system or email. If the manuscript is not published in the Journal, this release will not take effect.

The sole responsibility for the whole content (s) of the article remains only with the corresponding author. However, Editor would reserve the right to adjust the style to certain standards of uniformity before publication.

CONFLICT OF INTEREST DISCLOSURE FORM

Conflict of Interest is defined as a set of conditions in which professional judgment concerning a primary interest, such as the validity of research, may be influenced by a secondary interest, such as financial gain. A Conflict of Interest Disclosure is an agreement or notification from the authors that they have not been paid for the work, or if they have, stating the source of their payment. The purpose of Conflict of Interest Disclosure form is to provide readers of authors' manuscript with information about authors' interests that could influence how the authors receive the work. The corresponding author (on behalf of all co-authors) should submit a conflict of interest disclosure form and is responsible for the accuracy and completeness of the submitted manuscript. Conflict of Interest Disclosure form can be signed by the corresponding author on behalf of all co-authors and stating that the submitted manuscript is the authors' original work, has not received prior publication and is not under consideration for publication elsewhere, permission has been received to use any material in the manuscript much as tables, figures etc. or no permissions have necessary to publish the authors' work.

1. Name of the corresponding author

2. Affiliation including e-mail and phone number

3. Manuscript Title

4. Do the authors or authors' institution at any time receive payment or services from a third party (government, commercial, private foundation, etc.) for any aspect of the submitted manuscript (including but not limited to grants, data monitoring board, study design, manuscript preparation, statistical analysis, etc.)?

   Are there any relevant conflicts of interest? Yes / No

5. Do the authors have any patents, whether planned, pending or issued, broadly relevant to the work?

   Are there any relevant conflicts of interest? Yes / No

6. Are there other relationships or activities that readers could perceive to have influenced, or that give the appearance of potentially influencing, what the authors' information in the submitted manuscript?

   Are there any relevant conflicts of interest? Yes / No

7. Are there any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies or not.

   Are there any relevant conflicts of interest? Yes / No

Corresponding Author Signature | Print Name | Date

AUTHORSHIP FORM

By completing and signing the following statements, the corresponding author acknowledges and accepts the responsibility on behalf of all contributing authors, if any, concerning Authorship Responsibility.

Manuscript title:

Corresponding author:

Affiliation:

Email:

Phone No:

By signing and filling this form, the corresponding author certifies that each author has met all criteria below (A, B, C, and D) and indicates each author general and specific contributions by listing his or her name next to the relevant section.

A. I certify that

- The manuscript is authentic and valid and that neither this manuscript nor one with considerably similar content under my authorship has been published or is being considered for publication elsewhere, except as described in an attachment, nor copies of closely related manuscripts are provided.
- I will provide the data or will contribute fully in providing and obtaining the data on which the manuscript is based for examination by the editors or their assignees, if requested.
- Every author has agreed to allow the corresponding author to serve as the primary correspondent with the editorial office, to review the edited manuscript and proof.

B. Each author has given final approval of the submitted manuscript.

C. Each author has participated sufficiently in the work to take public responsibility for the whole content.

D. Each author qualifies for authorship by listing his or her name on the appropriate line of the categories of contributions listed below. List appropriate author next to each section – each author must be listed in at least 1 field. More than 1 author can be listed in each field.

- conception and design
- acquisition of data
- analysis and interpretation of data
- drafting of the manuscript
- critical revision of the manuscript for important intellectual content
- statistical analysis
- obtaining funding
- administrative, technical, or material support
- supervision
- no additional contributions
- other (specify)

Corresponding Author Signature **Print Name** **Date**

CHANGE OF AUTHORSHIP FORM

Manuscript Title:

Corresponding Author:

Please check all that apply.

☐ New author(s) have been added.

☐ There is a change in the order of authorship.

☐ An author wishes to remove his/her name. An author's name may only be removed at his/her own request in writing.

ORIGINAL AUTHORSHIP

List ALL AUTHORS in the same order as the original (first) submission.

Print Name	Print Name
Name (1)	Name (6)
Name (2)	Name (7)
Name (3)	Name (8)
Name (4)	Name (9)
Name (5)	Name (10)

NEW AUTHORSHIP

List the ALL AUTHORS in same order as the new version.

Print Name	Print Name
Name (1)	Name (6)
Name (2)	Name (7)
Name (3)	Name (8)
Name (4)	Name (9)
Name (5)	Name (10)

I attest that:

1. The manuscript is not currently under consideration, in press, or published elsewhere, and the research reported will not be submitted for publication elsewhere until a final decision has been made as to its acceptability by the journal (posting of submitted material on a web site may be considered prior publication-note this in your cover letter).
2. The manuscript is truthfully original work without fabrication, fraud, or plagiarism.
3. I have made an important scientific contribution to the study and am thoroughly familiar with the primary data.
4. I have read the complete manuscript and take responsibility for the content and completeness of the manuscript and understand that I share responsibility if the paper, or part of the paper, is found to be faulty or fraudulent.

Corresponding Author Signature Name Date

SUBSCRIPTION FORM

Subscription form

Global Journal of Environmental Science and Management

Please enter my annual subscription to the Global Journal of Environmental Science and Management (GJESM), including 4 quarterly issues for the Year ..... Vol. ..... Nos.....

	Domestic (Rials)	International (USD)
▪ Institutional	3,000,000	150
▪ Individual	2,000,000	100
▪ Student	1,000,000	80
▪ Single Copy	500,000	50

Name: **Tel.:** **Email:**

Mailing Address:

Payment method: Check or money order must be made in order of:
Account #. 0101834143005, Account name: J. Nouri
Bank Melli Iran, IAU Branch, Code 1017, Tehran, Iran

☐ Bank receipt enclosed

* Please allow 3 to 5 weeks for delivery

Please send this filled in order form along with the Bank receipt payment to:

Global Journal of Environmental Science
and Management
No. 2, Kouhestan Deadend, Janpour Street,
Darabad, Tehran 1956934461 Iran

CONTENTS

Volume 11, Issue 2, Spring 2025

1.	Removal of trihalomethanes from activated Napier grass-derived adsorbent using liquefied gas and chemical pretreatment	365
2.	Optimized removal of trivalent arsenic from aquatic environments using Prosopis juliflora seed biomass	391
3.	Projection of future temperature variations in river basins under climate change scenarios using general circulation models	403
4.	Dynamics prediction of land use changes using cellular automata and artificial neural network modeling	427
5.	Eco-friendly biocontrol of Phytophthora capsici in black pepper (Piper nigrum) using Burkholderia species	443
6.	Spatial heterogeneity of marine debris distribution on a tropical remote island shoreline	461
7.	Optimizing industrial and domestic water consumption efficiency for sustainable growth through data envelopment analysis	481
8.	Innovation in the blue economy and environmental sustainability in marine and fisheries strategy	497
9.	Social acceptance of water quality through decentralized greywater treatment using green wall system	519
10	Modeling the effects of land use change on agricultural carrying capacity and food security	533
11.	Balancing environmental quality and economic profitability for sustainable rice-soybean cropping system	555
12.	The impacts of land use and cover change on water quality of watershed basin	573
13.	Hydrodynamic simulation experiment of tidal pump in strait waters	593
14.	Ecological features of mangroves as indicators of seawater intrusion	609
15.	Ecological population dynamics, host preferences, and associated parasitoids of Bactrocera carambolae and Bactrocera papaya on fruits	631
16.	*Sesbania grandiflora* activated carbon as a high-efficiency stable and reusable adsorbent for sustainable fluoride removal	653
17.	A model designed for estimating biomass and carbon pool stock in over-mature plantations of teak; Tectona grandis	677
18.	Reducing hydrogen consumption in hybrid electric vehicles using aquila optimization algorithm	695
19.	Morphological and molecular monitoring of fishes in the waters of mangrove ecosystems	711
20.	Sustainable pest management with citronella oil for eco-friendly control of Aphis gossypii in chili plants	733
21.	Multi-dimensional perspectives on sustainability in domestic waste management	747
22.	The impact of land use change on morphological and anatomical adaptations of Rhizophora species	771
23.	Green chemistry approach to formaldehyde detection using fish albumin-modified gold electrodes	791
24.	Mathematical model of the territorial bioecological coefficient to evaluate the progress of the sustainable development goal	805
25.	A global perspective on sustainable pathways for biogas adoption	825