Quarterly Publication

ISSN 2383 - 3572

Global Journal of Environmental Science and Management

Volume 10, Special Issue, 2024

Global Journal of Environmental Science and Management (GJESM)

(QUARTERLY PUBLICATION)

OPEN ACCESS

Publisher and Editor in Chief
Professor J. Nouri
Tehran University of Medical Sciences,
Tehran, Iran
Email: editor@gjesm.net
nourijafar@gmail.com

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

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

Website Manager
M. Dorani
Sinaweb Management System

Editorial Contact Information
2, Kouhestan Deadend,
Janpour Street, Darabad Square,
Tehran, Iran
Phone: +9821-26105110
Email: gjesm.publication@gmail.com
editor@gjesm.net

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

Publication Center
GJESM Publisher
publisher@gjesm.net

Editorial Board

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

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

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

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

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 M.H. Sayadi; *University of Birjand, Birjand,* ***Iran***

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.

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 Impact Factor

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

CONTENTS

Volume 10, Special Issue 2024

1.	Optimal cropping patterns using linear programming and evaluation based on food-energy-water nexus **V. Hacısüleyman; M. Özger (TURKEY)**	1
2.	Dark septate endophytes symbiosis in Falcataria moluccana and its potency for forest and landscape restoration **Surono .; Yulianti .; K.P. Putri; D.J. Sudrajat; Y.M.M.A. Nugraheni; C. Sriherwanto; M.A. Syabana; N. Widyani; N. Yuniarti; M. Zanzibar; E. Rustam; R.U.D. Sianturi (INDONESIA)**	19
3.	The role of nutrient availability and resorption efficiency and their impact on nutrient conservation in mangroves **M.E.B. Gerona-Daga; R.A. MacKenzie; L.G. Sumabat-Dacones; C.F.P. Naputo; S.G. Salmo III (PHILIPPINES)**	37
4.	Phenol solutions recovery as water pollutants with eugenol cross-linked diallyl phthalate using supported liquid membrane **A.A. Kiswandono; N. Ningsih; A.V. Sindiani; Rinawati; H.I. Qudus (INDONESIA)**	53
5.	Impacts of environmental quality and employment resilience during the coronavirus disease 2019 recession and recovery **D.O. Ayuningsih; L. Hakim; A. Suryantoro; I. Mafruhah; S. Hassan; E. Gravitiani; N.Q. Fathoni; A.I. Hakim (INDONESIA/ MALAYSIA)**	71
6.	Nine circular strategy approach for the sustainable management of waste in the palm oil industry **S. Suprihatin; N.S. Indrasti; H. Prasetya; L. Agustina; E. Yulistika (INDONESIA)**	89
7.	Municipal panel data analysis for solid waste, local governments and citizen participation **P. Hernández Medina; D. Pinilla Rodríguez (ECUADOR)**	105
8.	Characterization of shallow groundwater in coastal aquifer of urbanized area using stable isotope and hydrochemical approaches **S. Satrio; R. Prasetio; E.R. Pujiindiyati; M.F. Ramadhani; P. Sidauruk (INDONESIA)**	123
9.	Environmentally friendly synthesis of nanoporous silica materials using quercetin as a morphogenetic agent **A.R. Zare Hoseinabadi; E. Rafiei Taqanaki; S. Hafez Ghoran; A.M. Amani; H. Kamyab; A. Razmfarsa; E. Khalili; M. Yusuf; S. Rajendran (IRAN/ MALAYSIA/ UK/ CANADA/ CHILE)**	137
10	Validation of heavy metals in geothermal to support water management practices and mitigation strategies **G.M. Idroes; D.P. Rezeki; K. Khairi; K. Khairan; R. Idroes; E. Suhartono; R. Prasetio; S.A. Rahman; S. Suhendrayatna (INDONESIA/ MALAYSIA)**	153
11.	Food waste reduction strategies in composting and recycling centers based on material flow analysis **S.C. Zahra; A.D. Anggrainy; Z. Mohd-Zaki; A.Y. Bagastyo (INDONESIA/ MALAYSIA)**	167
12.	Conversion of motorcycles to electric vehicles towards sustainable mobility **A.D. Santoso; H. Daulay; A. Priyanti; M. Silalahi; U.K. Yaumidin; N. Irawati; H. Sumartono; P. Astuti; A.R. Farandy; A. Parikesit; M.F. Manti; E. Indriasari; W. Joelijani; S. Wahyuni (INDONESIA)**	181
13.	A statistical approach to the water scarcity implications on food security **J. AlBtoosh; A. Abu-Awwad; N. Obeidat (JORDAN)**	201

CONTENTS

(Contintued)

14.	Exploring the potential of palm oil plantation waste for local communities using mixed methods **A. Ilhami; T. Hidayat; Riandi (INDONESIA)**	219
15.	Bibliometric analysis of biochar application for environmental management in agricultural sector **B.A. Bakar; Idawanni; A. Azis; S. Kurniawati; Y. Giamerti; Yardha; R. Purba; S. Abdullah; Jonharnas; D.R. Mustikawati; W. Chiari; E.A. Wikurendra (INDONESIA/ JAPAN/ MALAYSIA/ HUNGARY)**	237
16.	Radiation hazards from natural radionuclides contained in rice from former tin mining land **J. Mellawati; N. Madyaningarum; E.A. Fajrianshah; E.B. jumpeno; T.R.D. Larasati; N. Mulyana; E. Nurtjahya; K. Khotimah (INDONESIA)**	251
17.	Utilization of agricultural waste to reduce enteric methane emissions on livestock in tropical environment **Sulistyo; Pranoto; E. Mahajoeno; S.H. Pranolo; A. Sofyan; H. Herdian; B. Haryanto; R.H. Praptana (INDONESIA)**	263
18.	Sustainability index for eco-friendly cattle farming in dry climate regions **T. Simamora; M.N. Rofiq; L. Hutahaean; S. Sio; R. Hutapea; D. Irawan; Suryani; R. Diastuti; U.N. Thiyas; B.A. Correia; L.T. Correia (INDONESIA/ TIMOR-LESTE)**	279
19.	Spatial planning strategies and community behavior towards flood control **R. Dani; Sujianto; Nofrizal; B. Amin (INDONESIA)**	303
20.	Intervention strategy for sustainable waste management systems in developing countries using community of practice **Sunarti; M. Nuryana; W. Wiryanto; Buyamin; A. Aswin; C. Permatasari; J.H. Tjakraatmadja (INDONESIA)**	323

Global J. Environ. Sci. Manage. 10(SI): 1-18, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH PAPER

Optimal cropping patterns using linear programming and evaluation based on food-energy-water nexus

V. Hacısüleyman[1,2], M. Özger[3,*]

[1] *Graduate School, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey*

[2] *Vocational School, Construction Technology Department, Bilecik Seyh Edebali University, 11230, Bilecik, Turkey*

[3] *Hydraulics Division, Civil Engineering Department, Istanbul Technical University,34469 Maslak, Istanbul, Turkey*

ARTICLE INFO

Article History:
Received 24 May 2024
Revised 02 July 2024
Accepted 05 August 2024

Keywords:
Agricultural production planning
Crop pattern
Linear programming
Food energy water nexus
Optimization

ABSTRACT

BACKGROUND AND OBJECTIVES: Agriculture plays a significant role in the overall consumption of freshwater resources, accounting for approximately 70 percent of the total use. Energy is also essential at various stages of agriculture and the food chain. On a global scale, the agricultural and food industries account for approximately 30 percent of the overall energy consumption, with a significant portion derived from fossil fuel sources. This underscores the intricate interconnection between food, energy, and water resources. This study utilizes a linear programming model to determine the optimal cropping pattern while minimizing water usage in agriculture. This study's primary contribution lies in its dual approach: it identifies the optimal cropping patterns for a specified objective function through linear programming while simultaneously conducting a comprehensive analysis of these patterns by integrating considerations of food, energy, and water nexus.

METHODS: The constraints applied in linear programming involve maintaining nearly the same agricultural revenue, conserving the total cultivation area, and limiting the change intervals in cultivation area by 5 percent. Using linear programming, crop patterns were determined for the periods of 2017, 2025-2050, 2050-2075, and 2075-2100. In each scenario, calculations were conducted to assess water consumption, energy demands, agricultural income, and carbon dioxide emissions, all framed within the context of the food-energy-water nexus. The various scenarios were subsequently analyzed to assess their effects. An evaluation was conducted regarding the sustainability of water usage in agricultural production.

FINDINGS: All the scenarios examined resulted in lower water usage, reduced energy requirements, and decreased carbon dioxide emissions. Throughout various time periods, scenario 6, which permits a 5 percent variation in cultivation areas without imposing a total cultivation area limit, consistently proved to be the most favorable choice. It achieved an average reduction of 3.94 percent in water usage, 2.95 percent in energy requirements, and 1.62 percent in carbon dioxide emissions compared to the base scenario. Scenario 11, allowing for a 5 percent variation in cultivation areas while maintaining a total cultivation area limit, was evaluated as the second most effective scenario in terms of water conservation. It achieved an average reduction in water use of 3.45 percent, an average reduction in energy requirements of 1.85 percent, and a minimal reduction in carbon dioxide emissions of 0.11 percent across all time periods.

CONCLUSION: The outcomes of this study reveal that the proposed model can play a crucial role in advancing sustainable agricultural management strategies. The obtained results indicate that significant reductions in water usage, energy requirements, and carbon dioxide emissions can be achieved simply by modifying the crop pattern, while agricultural income remains largely at the same level. The imposition of a constraint requiring the total cultivation area to be equal to or greater than that of the baseline scenario in the linear programming model has been found to restrict the extent of these reductions.

DOI: 10.22034/gjesm.2024.10.SI.01

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

NUMBER OF REFERENCES
39

NUMBER OF FIGURES
6

NUMBER OF TABLES
6

*Corresponding Author:
Email: *ozgerme@itu.edu.tr*
Phone: +90 53249 57581
ORCID: 0000-0001-9812-9918

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

The interconnections among the systems of water, energy, and food are significant. Water plays a crucial role in the production of energy, whereas energy is vital for the processes of accessing, treating, and distributing water resources. Both energy and water play crucial roles in agriculture and raising livestock. Understanding this interrelationship is crucial, as a malfunction in one system has the potential to affect the functioning of the others. Understanding the intricate and ever-changing relationships among water, energy, and food is crucial for effectively managing these limited resources sustainably. The Sustainable Development Goals for 2030, established by the United Nations in 2015, place significant emphasis on ensuring food and water security, delineating a total of 17 objectives aimed at promoting sustainable development. Goal 2 focuses on eliminating hunger, ensuring food security, achieving adequate nutrition, and promoting sustainable agriculture. Goal 6 aims to ensure the availability of clean water and sanitation for all, alongside sustainable management of water resources (United Nations, 2015). Agriculture stands as the foremost user of the Earth's freshwater reserves, constituting roughly 70 percent (%) of the world's freshwater withdrawals and utilizing about 30% of global energy (FAO, 2011). The agricultural production sector is widely recognized for its significant consumption of water resources. The complex relationships between water, food, and energy highlight concerns associated with this sector. The optimal cultivating pattern for a specific land area to restrict water use to a certain level is one of the most important topics for sustainability of water in agricultural production. The implementation of effective optimization strategies for crop area planning is essential and beneficial for the managing agricultural water resources. They facilitate the allocation of water to different crop areas, ensuring the achievement of sustainability objectives (Zeng *et al.,* 2010). Linear programming (LP) serves as a widely utilized technique for determining the most efficient crop arrangement within a given agricultural landscape. Various researchers have utilized LP models to determine the optimal cropping patterns based on the existing resources and constraints. Singh *et al.* (2001) estimated the irrigation water needs for main crops and the total water available from both canal and groundwater sources within the Shahi Distributory command area. A linear programming model was developed to identify the optimal cropping pattern that maximizes net profit under different levels of water availability. Wheat emerged as the most consistently profitable crop in this area. Georgiou and Papamichail (2008) created a non-linear programming model incorporating an integrated soil water balance. This model establishes the most effective reservoir discharge rates, distributes irrigation resources among different crops, and determines the ideal crop arrangement for agricultural output. Bhuvandas *et al.* (2010) introduced a LP model to optimize crop area allocation within the Ukai reservoir command area. The objective is to optimize the overall relative yields of all crops cultivated in the irrigated area, taking into account different levels of water availability. Gadge *et al.* (2014) created a LP model that considered the available water resources and proposed a diverse cropping pattern aimed at maximizing profits. The newly developed methodology was subsequently evaluated against the current cropping pattern. Osama *et al.* (2017) developed a linear optimization model aimed at maximizing the yearly net return in Egypt's three old regions. The analysis encompasses data from 28 crops spanning five years, from 2008 to 2012. The model incorporates regional differences in agricultural practices, including variations in crop types, irrigation needs, crop productivity, and food consumption patterns. In the study, crop types are divided into two categories: non-strategic and strategic crops. The model takes into account the regional disparities in agricultural methodologies, which encompass differences in crop varieties, irrigation requirements, levels of crop yield, and patterns of food consumption. Crops like tomatoes, which yield higher net returns, have observed a considerable increase in their allocated land. Daghighi *et al.* (2017) used LP to create a water resource planning model aiding decision-makers in selecting an optimal crop arrangement, maximizing surface water utilization, and effectively distributing water among various crops to mitigate water scarcity's adverse impacts. Over a five-year span, the model was utilized to account for gradual changes, identifying the most suitable water usage pattern from the available resources. Findings indicate a potential for gradual enhancement in rectifying the negative water balance to eventually achieve positive. Imron and Murtiningrum (2021) aimed to achieve optimal

cropping areas and maximize benefits through the optimized allocation of irrigation water, considering dependable discharge and existing land area. The researchers investigated a range of cropping patterns to identify the most effective crop area by employing linear programming for the allocation of irrigation water. Kumar *et al.* (2022) employed a LP model to suggest cropping patterns, taking into account the rotational policy of the Bhadra reservoir canal system. The model integrates various constraints, including the availability of water and land, the decisions made by farmers, and the suitability of soil, to derive a cropping pattern that seeks to optimize net benefits. The food-energy-water (FEW) nexus is recognized as a practical concept used to describe the interconnected nature of global resource systems. The nexus approach provides a comprehensive analysis of the interconnections between human activities and environmental factors, facilitating the integrated management of natural resources across multiple sectors and levels (FAO, 2014). Especially in recent years, this approach has gained importance due to the consideration of preserving fundamental natural resources and climate variability. The use of the FEW nexus approach, addressing issues related to resources in water, energy, and food systems, gained momentum in the late 2000s. Considered as a globally significant international event that increased attention to the nexus approach, the "Bonn 2011 Nexus Conference: The Water-Energy and Food Security Nexus – Solutions for a Green Economy," marked the first major FEW nexus gathering. This conference involved the participation of various major groups, including the private sector, and is recognized for boosting awareness of the nexus approach on a global scale (Leck *et al.,* 2015). The Bonn 2011 Nexus Conference (Hoff, 2011) provided guidance toward understanding nexus interactions. El-Gafy *et al.* (2017) performed a comparative analysis of nexus and non-nexus methodologies to develop an optimal cropping pattern that incorporates water, energy, and economic dimensions. Their assessment of linear optimization techniques revealed that the nexus approach, which integrates considerations of water, food, and energy, provides a holistic framework for determining cropping patterns that reduce water and energy consumption while enhancing agricultural net returns. Chen *et al.* (2018) constructed a multi-region input-output model to analyze the global land-water nexus. The study concentrated on monitoring the worldwide patterns of agricultural land utilization and freshwater usage, in addition to examining the productivity of land and the water needs associated with various crops. Tian *et al.* (2018) systematically improved resource use efficiencies within the FEW nexuses to promote sustainable agriculture. They employed a conceptual model within a decision support system, underscoring the importance of integrated management across agricultural systems. Li *et al.* (2019) developed an optimization framework designed to allocate resources effectively for the sustainable management of the agricultural FEW nexus, especially in the face of uncertain conditions. Their model enables policymakers to identify optimal policy options regarding water, energy, and land resources to achieve maximum economic return while minimizing environmental impacts. Yuan and Lo (2020) introduced a systematic approach aimed at developing an extensive array of interconnected indicators pertinent to each sector within the FEW nexus. These indicators enable the analysis of specific issues and the formulation of region specific and national solutions. Abdi *et al.* (2020) conducted a comprehensive review of recent research on FEW nexus. In pursuit of this objective, considerable attention was directed towards the available statistics, accompanied by an examination of key studies that have emerged in this domain, particularly given that nearly ten years have elapsed since the initial concept was introduced. The discussion included actions policymakers need to take according to the nexus approach, along with important challenges and opportunities for implementation, concluding with future projections. Saray *et al.* (2022) conducted a study aiming to evaluate the water-energy-food nexus and carbon dioxide (CO_2) emissions in a farm situated in Northwest Iran. The study analyzed six essential indicators, which encompassed the energy input-output ratios for seven different crop varieties, as well as assessments of water and energy usage, productivity levels, and economic efficiency. The water-energy-food nexus index, derived from these indicators, demonstrated that silage corn had the highest value, indicating its superior performance, while potato showed the lowest value. Optimization assessments highlighted barley, rapeseed, silage corn, and wheat as the most successful crops under the study's conditions. The study conducted by Kamyab *et*

al. (2023) focused on the application of cutting-edge technologies, such as artificial intelligence and big data analytics, to mitigate the challenges inherent in data acquisition that are typically encountered with traditional water resource management practices.. They also outlined forward-looking directions for utilizing these methods to achieve optimal water resource allocation. A review of the existing literature reveals that significant research efforts have been directed towards the optimization of agricultural production as well as FEW nexus framework. Most optimization studies using LP method focus on maximizing annual net profit and optimally allocating water or land among various crops. Given that agricultural water usage constitutes a significant portion of overall water consumption, there exists a notable lack of research focused on minimizing the water footprint associated with this sector. This study aims to fill the existing gap by identifying the most appropriate cropping patterns, with a primary focus on minimizing water consumption as the objective function. Additionally, it intends to evaluate the effects of these cropping patterns on various factors, including energy demand, agricultural income, and CO_2 emissions, utilizing the FEW nexus framework. The main novelty of this study is the integration of FEW nexus based assessment into the determination of optimal crop patterns. In this study, the LP model was used to identify optimal cropping patterns that minimize agricultural water consumption. Then, using the cropping patterns obtained with LP, water usage, energy consumption, agricultural revenue and CO_2 emission parameters were calculated under different scenarios based on the FEW nexus and the scenarios were evaluated comparatively. This study seeks to explore the possible water conservation outcomes that may be realized through various scenarios in agricultural production. This study aims to optimize the distribution of irrigation water based on the available water supply, enhancing agricultural revenue by considering constraints related to crop area, cropping patterns, and water needs. The study has been carried out in Istanbul region of Turkey in 2024.

MATERIALS AND METHODS

The core techniques applied in this study consist of LP and the FEW nexus model. In this section, the LP method, selected as the most suitable option for determining optimal cropping patterns based on a specific objective function within certain constraints, is explained in detail along with the FEW nexus approach. The study area is also characterized by the presentation of geographical information and data pertaining to agricultural production.

Linear programming

Linear programming stands as a pivotal advancement in recent history, offering problem-solving capabilities across various disciplines (Simonovic, 1992). The concept of linear programming (LP) was first introduced by George Dantzig in 1947, along with the Simplex algorithm, which is extensively utilized for solving linear problems. In linear programming, it is crucial that both the objective function and the constraints maintain a linear form (Dantzig, 1963). While, real-life scenarios often present nonlinear complexities, linear models serve as effective approximations. Despite this, LP offers several notable advantages, including its efficiency in handling large-scale problems, the capability to converge to global optima, and a well-established duality theory beneficial for sensitivity analysis (Labadie, 2004). Typically, these models allow for an easy implementation process for users and can be effectively solved using current linear programming solvers, thus obviating the need for initial solutions provided by the user. Thanks to computer programs capable of solving LP problems, LP has become widely regarded as one of the most utilized optimization algorithms across various practical applications. It serves to assess and appraise alternative strategies, designs, and administrative approaches in agriculture, business, commerce, education, engineering, finance, government sectors (civil and military), and numerous other domains. When both the objective function, which consists of decision variables, and all constraints are linear, the model is identified as a LP model. The typical format of a LP model follows the structure given in Eqs. 1 to 3 (Loucks and van Beek, 2017).

$$Maximize\,or\,minimize\,Z = \sum_j c_j x_j \tag{1}$$

Subject to the restrictions,

$$\sum_j a_{ij} x_j \le or \ge b_i \;\; for\, i = 1,2,3,\ldots,m \tag{2}$$

And

$$x_j \geq 0 \quad for\ j = 1,2,3,\ldots,n \tag{3}$$

The fundamental terminology used in a LP model can be encapsulated through the following explanations. The function that undergoes maximization or minimization, expressed as $c_1x_1 + c_2x_2 + \cdots + c_nx_n$, is named as the objective function. Correspondingly, the restrictions concerning non-negativity are referred to as non-negativity constraints (or non-negativity conditions) (Hillier and Lieberman, 2010). If a model adheres to this general structure, numerous LP software tools are available to determine the "optimal" values for all the unknown decision variables x_j. The majority of commercial LP software integrates non-negativity constraints into their solution algorithms, thereby eliminating the need to explicitly specify these conditions for each individual applications (Loucks and van Beek, 2017). The LP model used in this study was developed to obtain the optimal cropping pattern that minimizes water use in agricultural production. An essential limitation within the model asserts that the agricultural revenue attained must be no less than the existing revenue obtained from the available dataset. Another constraint is the addition of upper and lower limits to prevent too large or too small changes in the planting areas allocated for agricultural crop types to meet food demand adequately. The current study explored two separate conditions: the enforcement of the constraint that requires the total area under cultivation to be equal to or greater than the available total cultivation area, and the scenario in which this constraint is disregarded.

Food, energy, water nexus

The term "nexus" broadly describes a system in which interconnected elements interact through feedback loops, necessitating the analysis of these elements together to comprehend their interdependencies (Caputo *et al.,* 2021). This idea highlights the fact that these elements are not independent entities; instead, they are closely interconnected, suggesting that changes in one element can significantly impact the others (Ansari *et al.,* 2023). The water-food-energy nexus was argued by Kurian (2017) to rely on robust scientific foundations, with the challenges associated with this approach highlighted, including concepts like synergies, trade-offs, and optimizing resource use. Water, energy, and food represent three interrelated resources, and the decision-making processes concerning these resources require a thorough analysis of the trade-offs involved. Water is an essential component in the production of agricultural goods. Energy is also required for various agricultural operations, including the use of tractors and farm tools, transportation of agricultural products, pumping groundwater, and conveying surface water, among other field-related processes. A lack of resources or their overexploitation can cause disruptions in other areas, which may jeopardize their stability and functionality. Maintaining a balance among these resources is crucial to ensure their security (Mohtar and Daher, 2012). Understanding the interdependency among these resources requires quantifying their connections through data-centric and quantitative modeling approaches (Degirmencioglu *et al.,* 2019). The application of modeling techniques centered on the WEF nexus can enhance the consistency of decision-making processes aimed at developing sustainable resource allocation strategies. In earlier studies, the WEF Nexus Tool 2.0 was established as a collaborative platform for the assessment of various scenarios, with the objective of determining effective strategies for sustainable resource allocation. This tool enables the creation of diverse scenarios dependent on different conditions of water, energy, and food resources. While resource analyses generate outputs in terms of national-level resource requirements, consumptions, and carbon emissions, creating scenarios at a regional or watershed level is necessary to obtain specific interactions among resources in that particular region (Mohtar and Daher, 2014). Through basin-specific research, optimal crop pattern scenarios are developed that enhance water security for the crops cultivated within the basin, allowing for the calculation of outputs associated with each scenario. These can be listed as water use, energy use, CO_2 emission, agricultural revenue. For this purpose, each scenario is determined by taking into account the changes that can be seen in the agricultural crop pattern depending on water requirements and spreadsheets are created for these scenarios. The need for water is a consequence of agricultural crop production, with each agricultural crop type requiring a specific amount of irrigation water. The total

water required to cultivate agricultural crops in the watershed can be met from various sources such as surface and groundwater. The volume of water used in livestock production is aggregated with the water necessary for the growth of agricultural crops, thereby facilitating the calculation of the comprehensive water requirements for agriculture. The average daily water requirement per animal is taken into account for both large and small livestock regarding their water consumption. The total agricultural water consumption is obtained by summing up the water needs for crops and livestock, using Eqs. 4 to 6 (Kulat *et al.,* 2019).

$$W_c = \sum_i W_{c_i} \; L_i \tag{4}$$

$$W_l = \sum_i W_{l_i} \; N_i .365 \tag{5}$$

$$W_T = W_c + W_l \tag{6}$$

Where, L_i is the land allocated for the specific crop, W_c is the total need for all crops for irrigation, N_i is the number of large and small livestock, W_l is the total livestock water requirements annually and W_T is the total agricultural water requirement.

Within the watershed, the energy demand is crucial for diverse farming operations that occur during the production phase in the fields, in addition to facilitating water supply from various sources. Energy requirements related to the use of surface or groundwater for irrigation are calculated based on the energy footprint values for each source type. Energy demands in agricultural practices encompass a range of activities, including soil preparation, planting, cultivation, harvesting, fertilization, and various other agricultural operations. The assessment of energy requirements is performed individually for each type of agricultural crop. The overall energy demand for agricultural operations is derived from the cumulative energy needs of all crops within the region, which is determined by analyzing fuel consumption across all stages of production, from soil preparation to harvesting, for each specific. The fuel consumption required for each agricultural crop type throughout these processes, multiplied with the cultivated area, is used to calculate energy requirements. The total energy requirement is obtained by summing the requirement for water conveyance and farming operations, using Eqs. 7 to 9 (Kulat *et al.,* 2019).

$$E_T = E_{\mathrm{sw}} + E_{\mathrm{gw}} + E_{\mathrm{fo}} \tag{7}$$

$$E_{sw} = \alpha_{sw} \times V_{sw} \tag{8}$$

$$E_{gw} = \alpha_{gw} \times V_{gw} \tag{9}$$

Where, E_T is total energy requirement, E_{sw} is the energy need for conveyance of surface water, E_{gw} is the energy need for pumping of groundwater and E_{fo} is the energy need for farming operations. α is the energy needed for unit volume of water and V is the volume of water used for irrigation depending on water type.

CO_2 emissions are used as another parameter to evaluate the sustainability of a scenario. CO_2 emissions primarily result from energy consumption. The scenario presents different energy types, each characterized by distinct coefficients that denote the CO_2 emissions generated, expressed in tons for every unit of energy utilized. CO_2 emissions for each type of energy consumption is evaluated separately and then aggregated, using Eq. 10 (Degirmencioglu *et al.,* 2019).

$$CO_2 = \sum_i E_i \, \Delta_i \tag{10}$$

Where, E represents the various types of energy consumption and Δ represents tons of CO_2 per unit energy consumption.

Agricultural revenue is considered as a key parameter for financial assessment of each scenario. Total agricultural revenue can be calculated by using the total production values and unit market prices for each agricultural product, using Eq. 11 (Degirmencioglu *et al.,* 2019).

$$\mathrm{R} = \sum_i P_i U_i \tag{11}$$

Where, R is the total agricultural revenue, P is the agricultural production and U is the unit market price for each agricultural product. The methodology used in this study is summarized in Fig. 1.

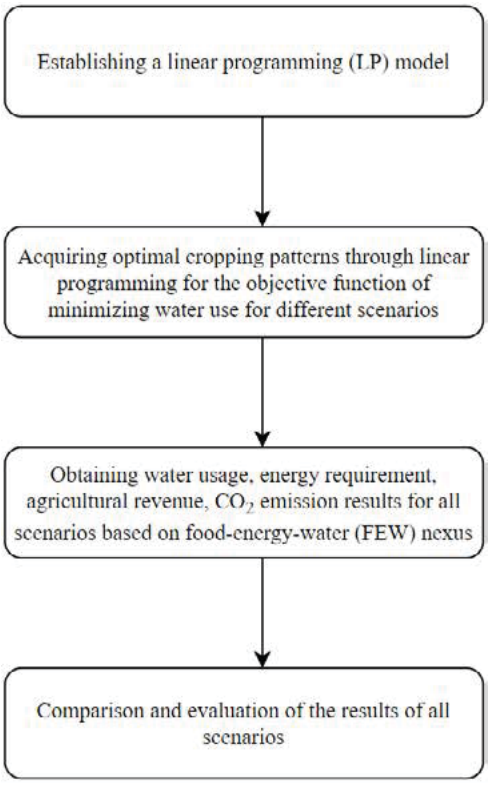


Fig. 1: Methodology of the study

Study area

The Gediz Basin is located in the western region of Turkey, specifically within the Aegean Region. It encompasses the territory that channels its waters into the Aegean Sea via the Gediz River and its associated tributaries, including the areas bordered by the Northern Aegean, Susurluk, and Küçük Menderes Basins. The location of Gediz Basin is shown in Fig. 2. The Gediz Basin covers an approximate area of 17,140 square kilometers (km²), constituting 2.2% of Turkey's total land area. The Gediz River, after which the basin is named, is approximately 275 kilometers (km) long and serves as the largest water source in the basin. Of the Gediz River, 175 km is situated in the province of Manisa, 40 km in Kütahya, 25 km in Uşak, and 35 km in İzmir. The annual average water potential is calculated to be 2.8 million cubic meters (m^3), with an average precipitation of 584 milimeters (mm). The total agricultural land area in the basin is approximately 1,774 km² (SYGM, 2019).

When examining the precipitation data of the basin, it is observed that the annual average precipitation values are higher around the Kemalpaşa and Demirci stations; in the northern parts of the basin, these values are lower compared to the vicinity of these two stations, and in the southern parts, they are observed to be the lowest. In the basin, the peak average monthly precipitation is recorded in the months of December and January, whereas the months of July and August experience the least average precipitation (SYGM, 2019). An analysis of temperature data across the basin reveals that the peak average monthly temperatures occur during the months of July and August, whereas the lowest average temperatures are noted in January. Agricultural production data for the six crop types used in the study were sourced from a report specifically prepared for the basin by the General Directorate of Water Management (SYGM). The data served as a foundational scenario for the development of various alternative scenarios, which were contingent upon the applied constraints. The outcomes related to water consumption, energy

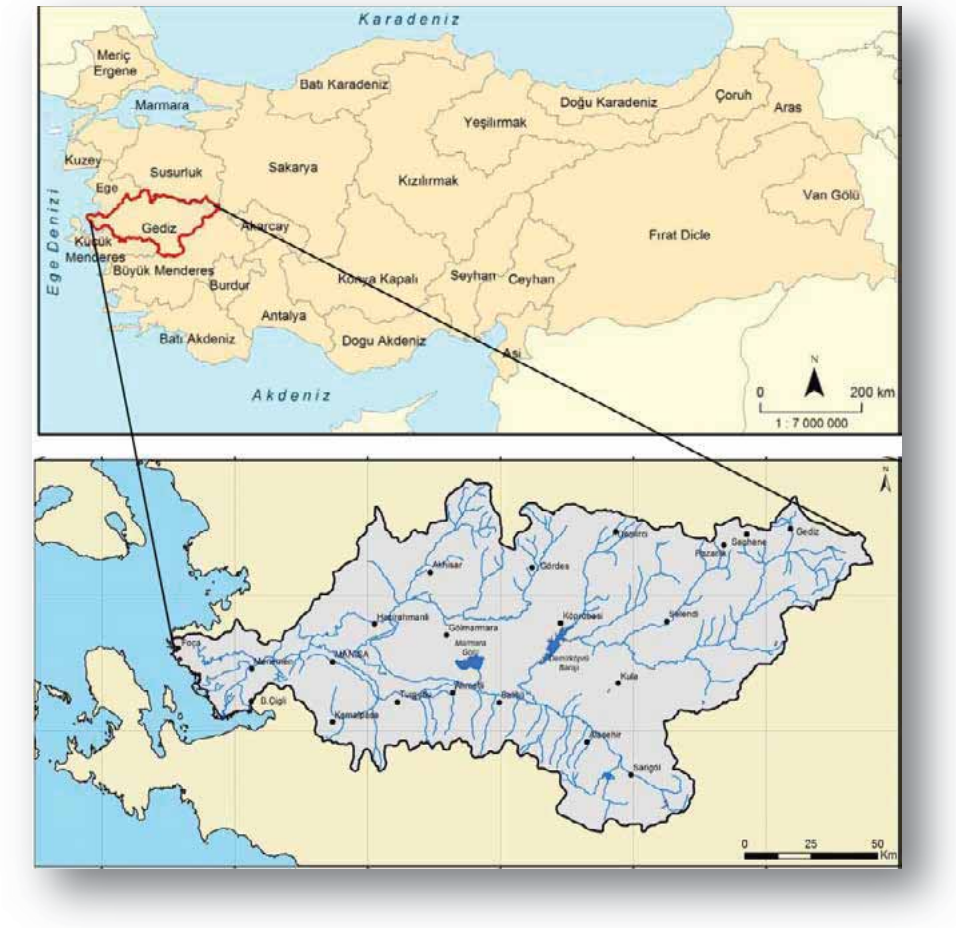


Fig. 2: Geographic location of the study area in Gediz Basin, Turkey

demands, and CO_2 emissions derived from this data were utilized as benchmarks for comparative analysis. The agricultural production data for the year 2017 obtained from the Gediz Basin Drought Report prepared by SYGM, along with annual production projections for future periods, are presented in Table 1 below (SYGM, 2019).

For each crop, fertilizer requirements, seasonal water needs, irrigation requirements, and fuel consumption based on tractor use in agricultural activities are shown in Table 2 in units of kilograms per hectare (kg/ha), cubic meters per hectare (m^3/ha), and liters per hectare (L/ha) (TurkStat, 2014).

Fuel consumption stands out as the most essential energy input in agricultural production processes, which is consistent with the observation that diesel is the main energy source utilized in Turkey's agricultural sector. The energy requirement varies according to the type of water source used. The energy requirements per unit volume of water are 0.4068 kilowatt hours per cubic meters (kWh/m^3) and 0.209 kWh/m^3 for groundwater and surface water (Degirmencioglu *et al.,* 2019). The emission of CO_2 is 0.00268 tons per liter from diesel use and 0.0026 tons per kilogram from the use of nitrogen, phosphorus and potassium fertilizers in agricultural production processes. (Wood and Cowie, 2004).

RESULTS AND DISCUSSION

In the context of this study, the LP method was

Table 1: The agricultural production data for the year 2017 and future period production projections

Planted crop	Production(tonnes) (2017)	Production(tonnes) (2025-2050)	Production(tonnes) (2050-2075)	Production(tonnes) (2075-2100)
Tomato	916950	1377834	2059207	2733990
Wheat	257807	291761	305572	350489
Corn	251641	325543	457944	621618
Grape	1098109	1368957	1836569	2307080
Cherry	108028	143965	206602	269594
Olive	206932	260526	341855	427850

Table 2: Various requirements and fuel consumption values for agricultural products

Planted crops	Nitrogen requirement (kg/ha)	Phosphorus requirement (kg/ha)	Potassium requirement (kg/ha)	Seasonal water requirement (m^3/ha)	Irrigation requirement (m^3/ha)	Gasoline consumption (L/ha)
Tomato	136,1	73,1	37,7	4028,5	2849,5	180,46
Wheat	120	40	0	4836,1	1182,9	65,6
Corn	272,7	166,6	0	2530	1794,9	159,1
Grape	55,8	51,5	41,6	6584,5	5396	225,55
Cherry	187,5	180,2	166,1	2094,4	1084,5	267,93
Olive	90	72	55,4	8928,4	0	50,93

applied to establish the ideal cropping patterns for the purpose of minimizing water use in agricultural practices. For the time periods 2017, 2025-2050, 2050-2075 2075-2100, the existing production and projection data for the basin were taken as the base or reference scenario. Subsequently, calculations pertaining to water consumption, energy demands, agricultural revenue, and CO_2 emissions for these time frames have been derived from data associated with the baseline scenario, utilizing the framework of the FEW nexus. Alongside the base scenario, changes in cropping patterns were evaluated as scenarios. In the derivation of these scenarios, LP was utilized to obtain optimal cultivation areas with the objective function of minimizing water usage, and constraints were set to be equal to or higher than the agricultural income amount in the base scenario, and allowing spatial changes in the cultivation areas within the ranges of 1%, 2%, 3%, 4%, and 5%. The implementation of upper and lower limits on the acreage designated for each crop serves to mitigate excessive fluctuations in land allocation, ensuring that changes remain within a manageable range while simultaneously addressing food demand. In crop pattern change scenarios where a total cultivation area constraint is also applied, LP was again used with the objective function of minimizing water usage, and constraints were set to be equal to or higher than the agricultural income amount in the base scenario, having the total cultivation area equal to or larger than that in the base scenario, and allowing spatial changes in the cultivation areas within the ranges of 1%, 2%, 3%, 4%, and 5%. By analyzing these two individual cases, the study seeks to enhance our understanding of how the existence or non-existence of a total cultivation area constraint influences the parameters generated within the FEW nexus framework. In naming the examined scenarios, the available data is taken as base or reference scenario for comparisons and denoted as Scenario 1. In LP, scenarios 2, 3, 4, 5, and 6 represent cases where there are no constraints on the total cultivation area, and spatial changes in cultivation areas for each crop are within the intervals of 1%, 2%, 3%, 4%, and 5%. Scenarios 7 through 11 represent instances in which a limitation is imposed on the overall cultivation area, taking into account spatial variations in cultivation zones within the ranges of 1%, 2%, 3%, 4%, and 5%. The cultivation area values obtained for the optimal crop pattern that minimizes water consumption using the LP method for each period are shown in hectares (ha) in Tables 3, 4, 5, and 6.

After obtaining different crop pattern scenarios with LP, water usage, energy requirement, agricultural revenue, and CO_2 emissions were calculated for these scenarios based on FEW nexus and compared for each scenario in the periods 2017, 2025-2050, 2050-2075, and 2075-2100. The findings derived from the

Table 3: The crop pattern obtained through LP for the year 2017

Cultivation Area (ha)	Tomato	Wheat	Corn	Grape	Cherry	Olive
Scenario 1	13354,4	93885,3	24534,9	61397,8	18806,4	93297
Scenario 2	13487,9	92945,7	24290,6	60784,3	18837,8	94229,6
Scenario 3	13621,4	92006,9	24045,3	60170,4	18820,9	95162,6
Scenario 4	13755	91068	23799,9	59556,4	18804,1	96095,6
Scenario 5	13888,5	90129,2	23554,5	58942,4	18787,2	97028,5
Scenario 6	14022,1	89190,3	23309,2	58328,4	18770,3	97961,5
Scenario 7	13417,8	93558,2	24290,6	60784,3	18995,2	94229,6
Scenario 8	13465,6	93248,7	24045,3	60170,4	19183,3	95162,6
Scenario 9	13513,4	92939,2	23799,9	59556,4	19371,3	96095,6
Scenario 10	13561,2	92629,7	23554,5	58942,4	19559,4	97028,5
Scenario 11	13609	92320,2	23309,2	58328,4	19747,5	97961,5

Table 4: The crop pattern obtained through LP for the period 2025-2050

Cultivation Area (ha)	Tomato	Wheat	Corn	Grape	Cherry	Olive
Scenario 1	20066,7	106250,3	31740,3	76541,5	25062,6	117460,3
Scenario 2	20267,3	105187	31424,3	75776,8	24979,9	118634,5
Scenario 3	20467,9	104124,5	31106,9	75011,3	24837,9	119809,1
Scenario 4	20668,6	103062	30789,5	74245,9	24695,8	120983,7
Scenario 5	20869,3	101999,5	30472	73480,5	24553,8	122158,3
Scenario 6	21069,9	100937	30154,6	72715,1	24411,8	123332,9
Scenario 7	20140,1	105831,9	31424,3	75776,8	25314,2	118634,5
Scenario 8	20194,4	105435,2	31106,9	75011,3	25564,8	119809,1
Scenario 9	20248,8	105038,5	30789,5	74245,9	25815,5	120983,7
Scenario 10	20303,1	104641,7	30472	73480,5	26066,1	122158,3
Scenario 11	20357,4	104245	30154,6	72715,1	26316,7	123332,9

Table 5: The crop pattern obtained through LP for the period 2050-2075

Cultivation Area (ha)	Tomato	Wheat	Corn	Grape	Cherry	Olive
Scenario 1	29990,2	111279,8	44649,4	102686,8	35967	154128,1
Scenario 2	30290	110166,2	44204,8	101660,8	35751,4	155668,9
Scenario 3	30589,9	109053,4	43758,3	100633,9	35454,1	157210,1
Scenario 4	30889,8	107940,6	43311,8	99607	35156,8	158751,4
Scenario 5	31189,7	106827,8	42865,3	98580,2	34859,5	160292,7
Scenario 6	31489,6	105715	42418,8	97553,3	34562,2	161834
Scenario 7	30088,1	110750,6	44204,8	101660,8	36328	155668,9
Scenario 8	30159,8	110251,4	43758,3	100633,9	36687,7	157210,1
Scenario 9	30231,4	109752,2	43311,8	99607	37047,4	158751,4
Scenario 10	30303,1	109253	42865,3	98580,2	37407,1	160292,7
Scenario 11	30374,8	108753,7	42418,8	97553,3	37766,7	161834

scenarios for the year 2017, along with a comparative analysis of these results, are presented in Fig. 3.

Comparing the results of the scenarios for the year 2017, the largest decrease in water usage, with a decrease of 23.4 million m^3 and a proportional decrease of 4.02% compared to the base scenario, occurred in scenario 6, which allows a 5% change in cultivation areas without a total cultivation area constraint, and in scenario 11, which allows a 5% change in cultivation areas with a total cultivation area constraint, where there was a decrease of 19.8 million m^3 and a proportional decrease of 3.4% compared to the base scenario. The analysis revealed that scenario 6 had the largest decline in energy requirements, with a reduction of 2.83%. This was closely followed by scenario 5 with a decrease of 2.26%. Agricultural revenue was almost equal in all scenarios. A decrease in CO_2 emissions occurred in all scenarios, with the highest decrease of 1.38% in scenario 6 and 1.1% in scenario 5. The findings derived from the scenarios analyzed for the years 2025 to 2050, along with a comparative assessment

Table 6: The crop pattern obtained through LP for the period 2075-2100

Cultivation Area (ha)	Tomato	Wheat	Corn	Grape	Cherry	Olive
Scenario 1	39817,7	127637,2	60607,5	128994,1	46933,1	192899,7
Scenario 2	40215,7	126359,8	60004,1	127705,3	46603,2	194828
Scenario 3	40613,9	125083,5	59398	126415,3	46167,5	196757
Scenario 4	41012	123807,1	58791,9	125125,4	45731,7	198686
Scenario 5	41410,2	122530,8	58185,8	123835,4	45295,9	200615
Scenario 6	41808,4	121254,4	57579,7	122545,5	44860,2	202544
Scenario 7	39940,7	127007	60004,1	127705,3	47404,3	194828
Scenario 8	40029,8	126415,6	59398	126415,3	47873,6	196757
Scenario 9	40118,9	125824,3	58791,9	125125,4	48342,9	198686
Scenario 10	40207,9	125232,9	58185,8	123835,4	48812,3	200615
Scenario 11	40297	124641,6	57579,7	122545,5	49281,6	202544

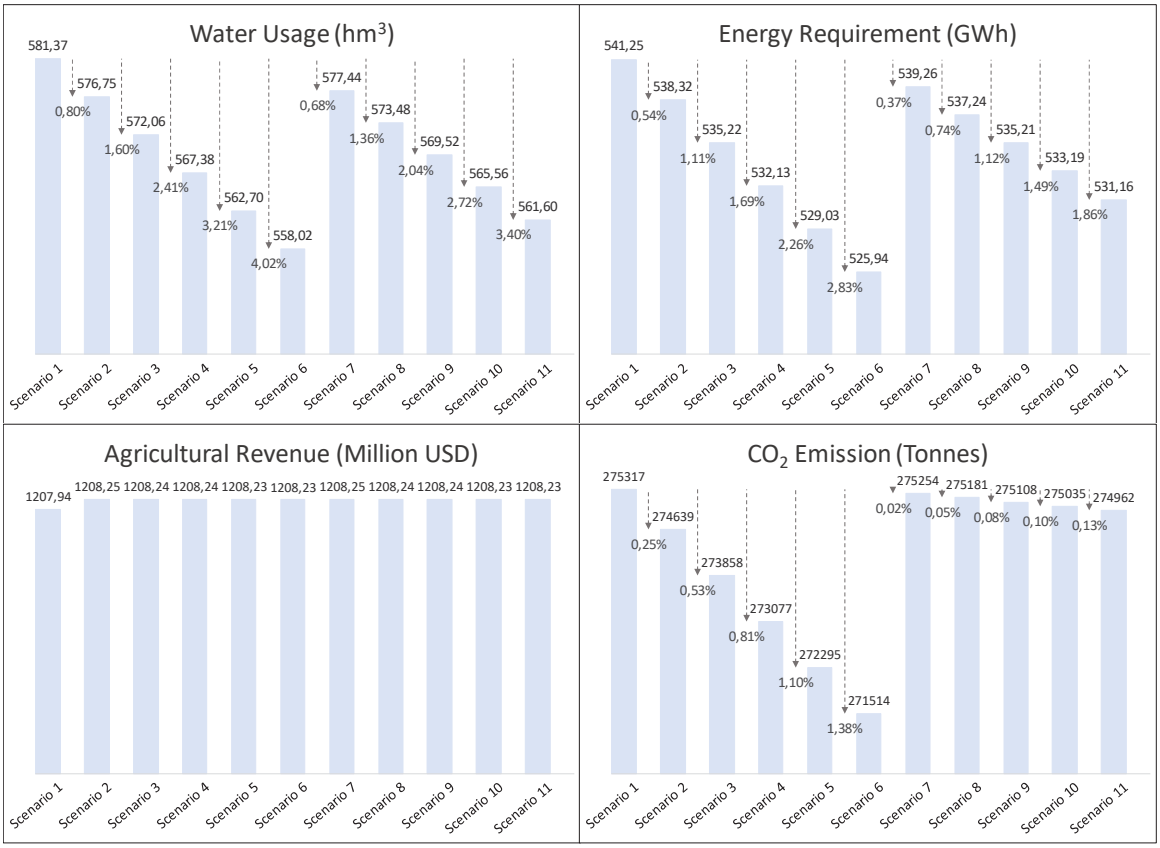


Fig. 3: Results and comparisons of the scenarios for the year 2017

of these results, are illustrated in Fig. 4.

The analysis of the scenarios projected for the period from 2025 to 2050 indicates that scenario 6 achieved the most pronounced reduction in water usage, with a total decrease of 28.8 million m³, representing a proportional decline of 3.96% against the base scenario. In contrast, scenario 11 recorded a decrease of 24.8 million m³, which corresponds to a proportional decline of 3.41% in comparison to the baseline scenario. The most substantial reductions in energy requirements were found in scenario 6, with a decrease of 2.95%, followed by scenario 5 with a decrease of 2.36%. Agricultural revenue exhibited a consistent pattern across all scenarios analyzed.

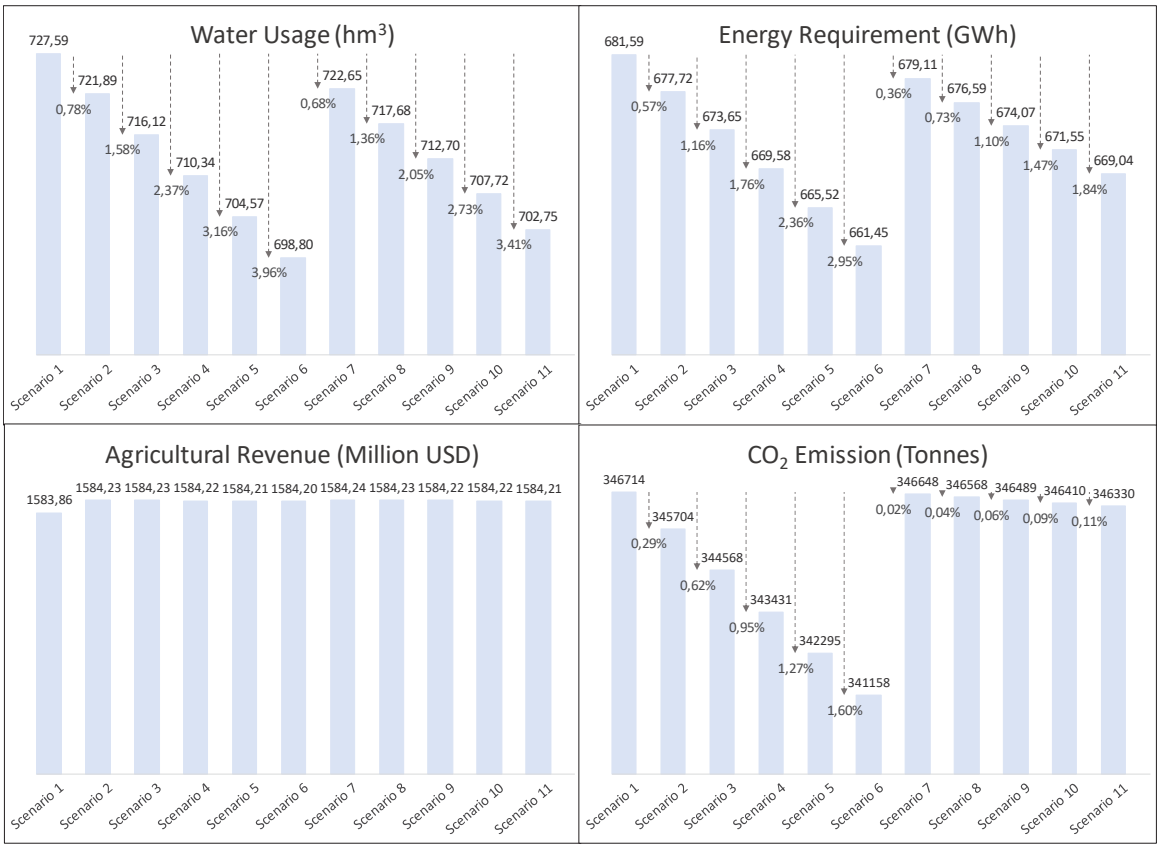


Fig. 4: Results and comparisons of the scenarios for the period 2025-50

Carbon dioxide emissions experienced a decline in every scenario, with the most pronounced reductions observed in scenario 6 at 1.6% and scenario 5 at 1.27%. Results obtained from the scenarios examined for the period 2050-2075 and comparisons of the scenario results are presented in Fig. 5.

Upon reviewing the outcomes for the 2050-2075 timeframe, it is evident that scenario 6 leads to the most significant reduction in water usage, totaling 37.2 million m³. This reduction reflects a proportional decrease of 3.89% when compared to the baseline. Scenario 11 exhibits substantial reductions, with a decrease of 33.3 million m³, reflecting a proportional decrease of 3.49% compared to the base scenario. The most notable decreases in energy requirements are found in scenario 6, with a reduction of 3%, and in scenario 5, with a decrease of 2.39%. Agricultural revenue exhibits a stable pattern across all examined scenarios. Notably, CO_2 emissions have experienced a decline in every scenario, with the most pronounced reduction occurring in scenario 6 at 1.7%, followed closely by a 1.35% decrease in scenario 5. Results obtained from the scenarios examined for the period 2075-2100 and comparisons of the scenario results are given in Fig. 6.

Upon reviewing the outcomes of the scenarios for the years 2075 to 2100, it is evident that scenario 6 achieved the highest reduction in water usage, totaling 46.6 million m³. This represents a proportional decline of 3.87% in comparison to the baseline scenario. Scenario 11 showed significant reductions, with a decrease of 42.1 million m³, representing a proportional decline of 3.5% compared to the base scenario. The greatest decreases in energy requirements were observed in scenario 6 with a reduction of 3.03%, and in scenario 5 with a decrease of 2.42%. Agricultural revenue showed a consistent pattern across all scenarios. Carbon

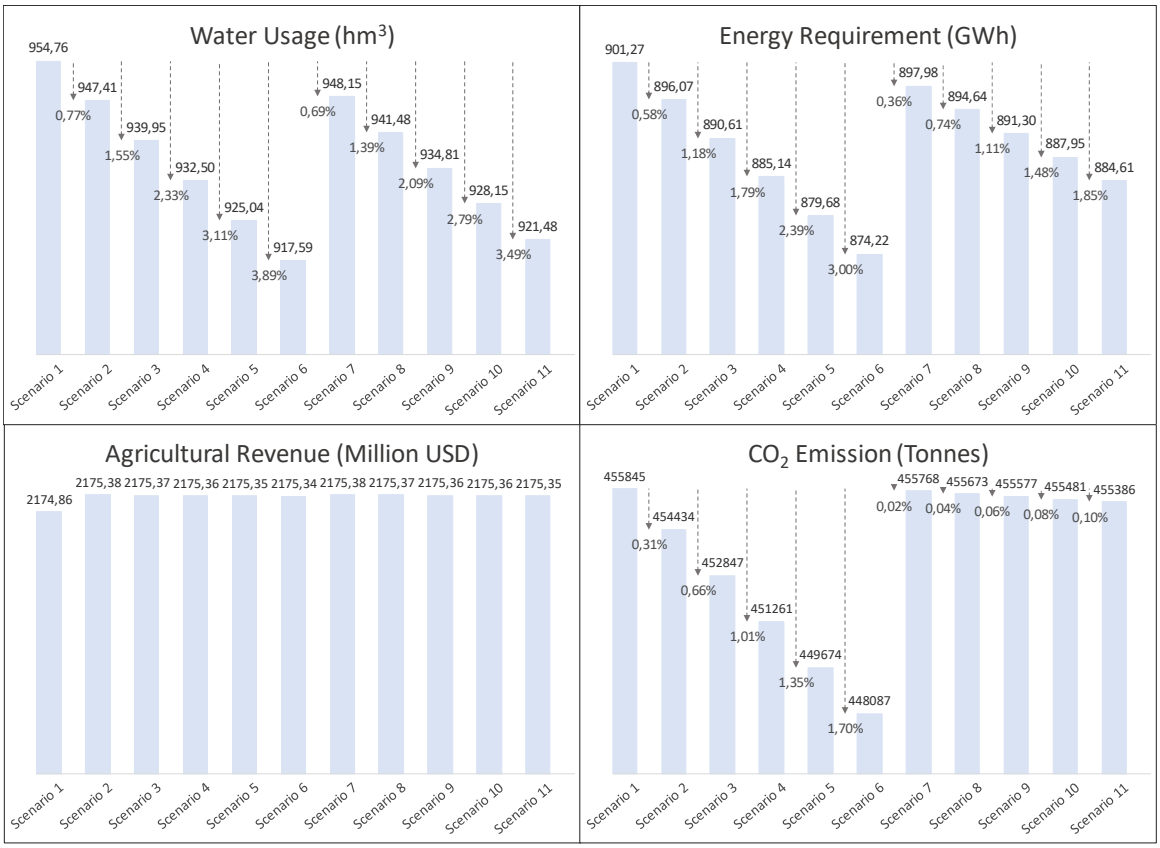


Fig. 5: Results and comparisons of the scenarios for the period 2050-2075

dioxide emissions decreased in every scenario, with the most significant reduction observed in scenario 6 at 1.78%, followed by a 1.42% decrease in scenario 5. In this study, a water-centered perspective is adopted, focusing on potential water savings that can be achieved in agricultural production while considering constraints such as maintaining the current agricultural income level, limiting changes in cultivation areas for each crop, and preserving the total cultivation area. The findings indicate that significant reductions in water consumption, energy demands, and CO_2 emissions can be realized by altering cropping patterns, with agricultural revenue remaining relatively stable. Different objectives and approaches may be prioritized in optimization models. Most of the previous studies have primarily concentrated on boosting income. A thorough analysis of the studies performed demonstrates that, even with differing aims, the constraints implemented exhibit significant similarities. Osama *et al.* (2017) focused on maximizing the total net benefit as the primary objective in determining the optimal cropping pattern, taking into account constraints such as water availability, total land area, and planting area over a five-year period from 2008 to 2012. After optimization, the gross net benefit increased by an average of 6.44% over the five-year period compared to the previous cropping pattern. Daghighi *et al.* (2017) selected increasing the profit to be made from the agriculture as target function using 2015 as the reference year and determined the optimal cropping patterns for every five-year interval from 2020 to 2040. The constraints imposed encompassed a maximum allowable variation of 20% in the areas designated for cropping, restrictions on the volume of irrigation water available, and the distribution of water resources contingent upon the specific types of crops being cultivated. The final net profit increased by 8% compared to the reference year. In their study, Kumar *et al.* (2022) employed

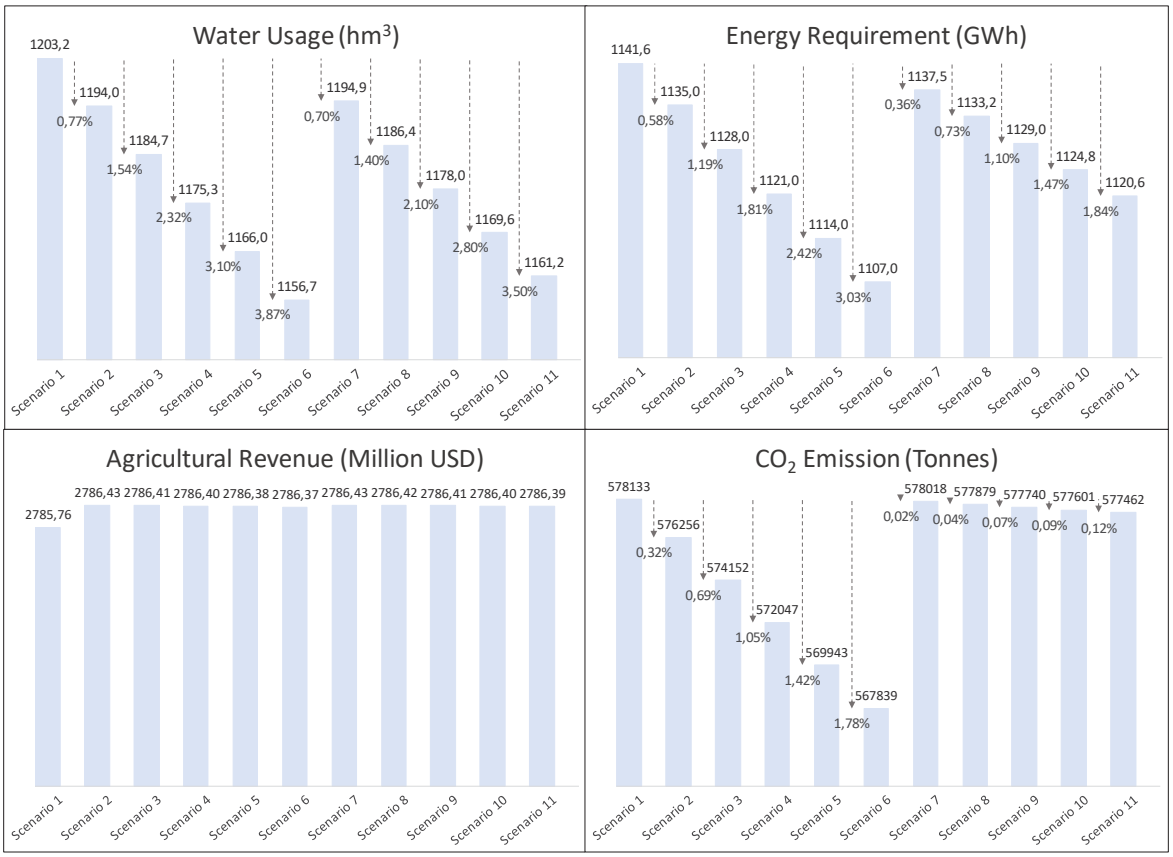


Fig. 6: Results and comparisons of the scenarios for the period 2075-2100

LP to maximize net returns and identify the optimal crop pattern while considering constraints related to water availability, total land area, farmers' crop preferences, crop acreage, and available fertilizers. Saray *et al.* (2022) developed and calculated a water-energy-food nexus index by analyzing water and energy consumption and productivity metrics, using data collected from a farm within their study area. Two distinct scenarios were examined to identify the most effective cropping patterns: the first aimed at enhancing the water-energy-food nexus index, while the second sought to reduce CO_2 emissions. Each scenario was constrained by limitations on the total area available for cultivation and the distribution of land across various crops. The approach focused on minimizing CO_2 emissions yielded better results in reducing water and energy consumption as well as CO_2 emissions. This approach also led to a decrease in food production. Tajbakhsh *et al.* (2018) proposed a comprehensive model for optimizing land allocation aimed at minimizing surface runoff and sediment load while maximizing net income. This model utilized weighted goal programming, the analytic hierarchy process, and multi-objective land allocation algorithms. Their approach resulted in a 16.78% reduction in sediment load and a 72.52% increase in net income, though it also led to a 0.22% increase in runoff volume. Hrytsiuk *et al.* (2019) applied Markowitz's optimal portfolio theory to redistribute existing grain crop areas with the goal of enhancing production efficiency. The findings of their analysis indicated that the profitability of crops adheres to a Laplace distribution instead of a normal distribution. Consequently, through optimization, they developed efficient frontiers for portfolios of cereal crop sown areas in the Rivne region by conducting numerical risk evaluations. The main limitations and uncertainties encountered in studies

aimed at determining the optimal cropping pattern can be listed as the need to make changes within certain limits in cultivation areas to ensure sufficient food supply, availability of land for agricultural activities, variability in economic paremeters, climatic characteristics for future periods. The emphasis on single-objective optimization within the context of various constraints to identify optimal cropping patterns represents a methodological limitation. In the realm of agricultural crop planning optimization, it is important to recognize the presence of multiple, often conflicting objectives. When dealing with these conflicting objectives, multi-objective methods that reflect various perspectives by assigning different priorities to the goals can also be preferred.

CONCLUSION

This study explored various scenarios to identify the most efficient cropping pattern aimed at reducing water consumption in agricultural production. LP was employed to identify the optimal cultivation zones for each crop type within the basin, aiming to minimize water consumption. In crop pattern change scenarios, constraints for LP were set to be equal to or higher than the agricultural income amount in the base scenario, having the total cultivation area equal to or larger than that in the base scenario, and allowing spatial changes in the cultivation areas within the ranges of 1%, 2%, 3%, 4%, and 5%. Following the analysis of crop patterns derived from linear programming for the years 2017, 2025-2050, 2050-2075, and 2075-2100, the study assessed water consumption, energy demands, agricultural income, and CO_2 emissions for each scenario. This evaluation was conducted within the framework of the FEW nexus, allowing for a comparative analysis of all scenarios. The key novelty of this study lies in incorporating FEW nexus based assessments into the determination of optimal planting patterns. The results and comparisons of the scenarios indicate that substantial decreases in water usage, energy needs, and CO_2 emissions can be accomplished solely through alterations in the crop pattern while the agricultural income largely stays at the same level. The introduction of a constraint within the LP model, which requires the total cultivation area to be at least as large as that of the baseline scenario, has been found to limit the possible reductions. In contrast, scenarios that do not impose a total cultivation area constraint demonstrated more favorable outcomes than those exhibiting comparable percentage changes but constrained by the total cultivation area requirement. Examining various scenarios with different rates of change in planting areas and observing corresponding reductions in agricultural water use, energy requirements and CO_2 emissions highlights the trade-offs involved. When the allowable percentage changes decreased, these output parameters showed smaller reductions, resulting in less favorable outcomes. An increase in the permissible percentage variations in crop acreage led to improved outcomes. An analysis of all time periods revealed that scenario 6 emerged as the most favorable, yielding an average reduction of 3.93% in water consumption, a 2.95% decrease in energy demands, and a 1.62% decline in CO_2 emissions relative to the baseline scenario. Scenario 11 achieved an average water usage reduction of 3.45% across all time periods, ranking it as the second-best scenario for water conservation, but it only managed an average reduction of 1.85% in energy requirements and a mere 0.11% reduction in CO_2 emissions. With a third-place ranking in water use reduction, Scenario 5 achieved an average decrease of 3.15% in water usage, a 2.36% reduction in energy needs, and a 1.29% decline in CO_2 emissions over all analyzed periods. Improvement in all of these outcomes with the proposed model is considered important in terms of contributing to the sustainable management of agriculture. The conclusions drawn from the study are perceived as delivering critical insights to those in decision-making roles, facilitating the advancement of sustainable agricultural production planning in the agriculturally rich areas of the Gediz Basin. Although the results of this study were obtained for a specific region, the applied methodology can be readily adapted for use in various other applications. The fundamental characteristics of linear programming (LP) dictate that the approach is centered around a singular objective function accompanied by linear constraint equations. For a more comprehensive analysis that considers multiple perspectives or approaches simultaneously, future research could benefit from multi-objective optimization to determine optimal cropping patterns.

AUTHOR CONTRIBUTIONS

V. Hacısüleyman performed the literature review, methodology development, interpretation and

visualization of the results and wrote the manuscript. M. Özger supervised the work, conceptualization and manuscript edition.

ACKNOWLEDGEMENT

The authors wish to thank all who assisted in conducting this work. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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

©2024 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

%	Percentage
CO_2	Carbon dioxide
FAO	Food and agriculture organization
FEW	Food-energy-water
GWh	Gigawatt hours
ha	Hectare
hm^3	Cubic hectometer
kg/ha	Kilograms per hectare
km	Kilometer
km^2	Square kilometer
kWh/m^3	Kilowatt hours per cubic meter
L/ha	Liters per hectare
LP	Linear programming
mm	Millimeter
m^3	Cubic meter
m^3/ha	Cubic meters per hectare
SYGM	General Directorate of Water Management
TurkStat	Turkish Statistical Institute
USD	United States dollar
WEF	Water-energy-food

REFERENCES

Abdi, H.; Shahbazitabar, M.; Mohammadi-Ivatloo, B., (2020). Food, Energy and Water Nexus: A Brief Review of Definitions, Research and Challenges. Inventions, 5: 56 **(14 pages).**

Ansari, A.; Wuryandani, S.; Pranesti, A.; Telaumbanua, M.; Ngadisih; Hardiansyah, M.Y.; Alam, T.; Supriyanta; Martini T.; Taryono, (2023). Optimizing water-energy-food nexus: achieving economic prosperity and environmental sustainability in agriculture. Front. Sustainable Food Syst., 7: 1207197 **(7 pages).**

Bhuvandas, N.; Mirajkar, A.B.; Timbadiya, P.V.; Patel, P.L., (2010). Optimization of Irrigation Area of Ukai Right Bank Main Canal-A Linear Programming Approach. AIP Conference Proceeding, 1324 (1): 127–129 **(3 pages).**

Caputo, S.; Schoen, V.; Specht, K.; Grard, B.; Blythe, C.; Cohen, N.; Fox-Kämper, R.; Hawes, J.; Newell, J.; Poniży, L., (2021). Applying the food-energy-water nexus approach to urban agriculture: From FEW to FEWP (Food-Energy-Water-People). Urban For. Urban Green., 58: 126934 **(12 pages).**

Chen, B.; Han, M.Y.; Peng, K.; Zhou, S.L.; Shao, L.; Wu, X.F.; Wei, W.D.; Liu, S.Y.; Li, Z.; Li, J.S.; Chen, G.Q., (2018). Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. Sci. Total Environ., 613–614: 931–943 **(13 pages).**

Dantzig, G.B., (1963). Linear Programming and Extensions, Princeton University Press, Princeton.

Daghighi, A.; Nahvi, A.; Kim, U., (2017). Optimal Cultivation Pattern to Increase Revenue and Reduce Water Use:

Application of Linear Programming to Arjan Plain in Fars Province. Agriculture, 7: 73 **(11 pages).**

Degirmencioglu, A.; Mohtar, R.H.; Daher, B.T.; Ozgunaltay-Ertugrul, G.; Ertugrul, O., (2019). Assessing the Sustainability of Crop Production in the Gediz Basin, Turkey: A Water, Energy, and Food Nexus Approach. Fresenius Environ. Bull., 28(4): 2511-2522 **(12 pages).**

El-Gafy, I.; Grigg, N.; Waskom, R., (2017). Water-food-energy: nexus and non-nexus approaches for optimal cropping pattern. Water Resour. Manage., 31: 4971–4980 **(10 pages).**

FAO, (2011). The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) - Managing systems at risk. The Food and Agriculture Organization of the United Nations, Rome and Earthscan, London. **(308 pages).**

FAO, (2014). The Water-Energy-Food Nexus. A new approach in support of food security and sustainable agriculture. Rome: Food and Agriculture Organization of the United Nations. **(28 pages).**

Gadge, S.B.; Gorantiwar, S.D.; Kumar, V.; Kothari, M., (2014). Linear programming approach for allocation of land and water resources in canal command area under surface method of irrigation-a case study. Int. J. Innovation Res. Sci. Eng. Technol., 3: 153–168 **(16 pages).**

Georgiou, P.E.; Papamichail, D.M., (2008). Optimization model of an irrigation reservoir for water allocation and crop planning under various weather conditions. Irrig. Sci., 26: 487–504 **(18 pages).**

Hillier, F.S.; Lieberman, G.J., (2010). Introduction to Operations Research, 9th. Ed. New York: McGraw-Hill Education.

Hoff, H., (2011). Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm: Stockholm Environment Institute. **(52 pages).**

Hrytsiuk, P.; Babych, T.; Mandziuk, O., (2019). Region sown areas portfolio optimization taking into account crop production economic risk. Glob. J. Environ. Sci. Manag., 5(Special Issue), 141-150 **(11 pages).**

Imron, F.; Murtiningrum, (2021). Optimization of irrigation water allocation by using linear programming: Case study on Belitang irrigation system. IOP Conference Series: Earth Environ. Sci., 653: 012023 **(9 pages).**

Kamyab, H.; Khademi, T.; Chelliapan, S.; SaberiKamarposhti, M.; Rezania, S.; Yusuf, M.; Farajnezhad, M.; Abbas, M.; Hun Jeon, B.; Ahn, Y., (2023). The latest innovative avenues for the utilization of artificial Intelligence and big data analytics in water resource management. Results Eng., 20:101566 **(11 pages).**

Kulat, M.I.; Mohtar, R.H.; Olivera, F., (2019). Holistic Water-Energy-Food Nexus for Guiding Water Resources Planning: Matagorda County, Texas Case. Front. Environ. Sci., 7: 3 **(13 pages).**

Kumar, S.B.; Ramesh, B.R.; Surendra, H.J., (2022). Optimal cropping pattern for a tail-end distributary canal of Bhadra command area using linear programming model. Model. Earth Syst. Environ., 8: 3897–3906 **(10 pages).**

Kurian, M., (2017). The water-energy-food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. Environ. Sci. Policy., 68, 97–106 **(10 pages).**

Labadie, J.W., (2004). Optimal Operation of Multireservoir Systems: State-of-the-Art Review. J. Water Resour. Plann. Manage., 130, 93-110 **(19 pages).**

Leck, H.; Conway, D.; Bradshaw, M.; Rees, J., (2015). Tracing the Water–Energy–Food Nexus: Description, Theory and Practice. Geogr. Compass., 9(8), 445-460 **(16 pages).**

Li, M.; Fu, Q.; Singh, V.P.; Liu, D.; Li, T., (2019). Stochastic multi-objective modeling for optimization of water-food-energy nexus of irrigated agriculture. Adv. Water Resour., 127: 209–224 **(16 pages).**

Loucks, D.P.; Van Beek, E., (2017). Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications, 1st. Ed. Cham, Switzerland: Springer International Publishing.

Mohtar, R.H.; Daher, B., (2012). Water, Energy, and Food: The Ultimate Nexus. In: Encyclopedia of Agricultural, Food, and Biological Engineering, CRC Press, Taylor and Francis Group, Boca Raton **(5 pages).**

Mohtar, R.H.; Daher, B., (2014). A platform for trade-off analysis and resource allocation: The water-energy-food nexus tool and its application to Qatar's Food Security. Chatham House. United Kingdom **(10 pages).**

Osama, S.; Elkholy, M.; Kansoh, R.M., (2017). Optimization of the cropping pattern in Egypt. Alexandria Eng. J., 56(4): 557–566 **(10 pages).**

Saray, M.H.; Baubekova, A.; Gohari, A.; Eslamian, S.S.; Klove, B.; Haghighi, A.T., (2022). Optimization of water-energy-food nexus considering CO_2 emissions from cropland: A case study in northwest Iran. Appl. Energy., 307: 118236 **(11 pages).**

Simonovic, S.P., (1992). Reservoir Systems Analysis: Closing Gap between Theory and Practice. J. Water Resour. Plann. Manage., 118 (3): 262-280 **(19 pages).**

Singh, D.K.; Jaiswal, C.S.; Reddy, K.S.; Singh, R.M.; Bhandarkar, D.M., (2001). Optimal cropping pattern in a canal command area. Agric. Water Manage., 50: 1-8 **(8 pages).**

SYGM, (2019). General Directorate of Water Management, Gediz Basin Drought Report. Ankara, Turkey.

Tajbakhsh, S.; Tajbakhsh, S.; Memarian, H.; Kheyrkhah, A., (2018). A GIS-based integrative approach for land use optimization in a semi-arid watershed. Glob. J. Environ. Sci. Manag., 4(1), 31-46 **(16 pages).**

Tian, H.; Lu, C.; Pan, S.; Yang, J.; Miao, R.; Ren, W.; Yu, Q.; Fu, B.; Jin, F.; Lu, Y.; Melillo, J.; Ouyang, Z.; Palm, C.; Reilly, J., (2018). Optimizing resource use efficiencies in the food-energy-water nexus for sustainable agriculture: from conceptual model to decision support system. Curr. Opin. Environ. Sustainable., 33: 104–113 **(10 pages).**

TurkStat, (2014). Turkish Statistical Institute, Crop Production Statistics.

United Nations, (2015). Transforming our world: the 2030 Agenda for Sustainable Development. Resolution **(35 pages).**

Wood, S.; Cowie, A., (2004). A review of greenhouse gas emission factors for fertiliser production. IEA Bioenergy Task 38 **(20 pages).**

Yuan, M.H.; Lo, S.L., (2020). Developing indicators for the monitoring of the sustainability of food, energy, and water. Renewable Sustainable Energy Rev., 119: 109565 **(9 pages).**

Zeng, X.; Kang, S.; Li, F.; Zhang, L.; Guo, P., (2010). Fuzzy multi-objective linear programming applying to crop area planning. Agric. Water Manage., 98(1): 134-142 **(9 pages).**

AUTHOR (S) BIOSKETCHES

Hacısüleyman, V., Ph.D. Candidate, [1]Graduate School, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey. [2]Instructor, Vocational School, Construction Technology Department, Bilecik Seyh Edebali University, 11230, Bilecik, Turkey.
- Email: *hacisuleymanv@itu.edu.tr*
- ORCID: 0000-0003-4340-2045
- Web of Science ResearcherID: AFE-2809-2022
- Scopus Author ID: 57219782026
- Homepage: https://avesis.bilecik.edu.tr/volkan.hacisuleyman

Özger, M., Ph.D., Professor, Hydraulics Division, Civil Engineering Department, Istanbul Technical University,34469 Maslak, Istanbul, Turkey.
- Email: *ozgerme@itu.edu.tr*
- ORCID: 0000-0001-9812-9918
- Web of Science ResearcherID: F-2935-2011
- Scopus Author ID: 6602721916
- Homepage: https://research.itu.edu.tr/tr/persons/mehmet-%C3%B6zger

HOW TO CITE THIS ARTICLE

Hacısüleyman, V.; Özger, M., (2024). Optimal cropping patterns using linear programming based on food-energy-water nexus. Global J. Environ. Sci. Manage., 10(SI): 1-18.

DOI: 10.22034/gjesm.2024.10.SI.01

URL: https://www.gjesm.net/article_714849.html

Global J. Environ. Sci. Manage. 10(SI): 19-36, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH PAPER

Dark septate endophytes symbiosis in Falcataria moluccana and its potency for forest and landscape restoration

Surono[1], Yulianti[2], K.P. Putri[2], D.J. Sudrajat[2], Y.M.M.A. Nugraheni[2,*], C. Sriherwanto[1], M.A. Syabana[3], N. Widyani[2], N. Yuniarti[2], M. Zanzibar[2], E. Rustam[2], R.U.D. Sianturi[2]

[1] *Research Center for Applied Microbiology, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor, Cibinong, Jawa Barat, 16911 Indonesia*

[2] *Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor, Cibinong, Jawa Barat, 16911 Indonesia*

[3] *Department of Agricultural Science and Center of Excellence for Local Food Innovation, Sultan Ageng Tirtayasa University, Serang, Indonesia*

ARTICLE INFO

Article History:
Received 21 March 2024
Revised 26 May 2024
Accepted 29 July 2024

Keywords:
Colonization
Dark septate endophytes (DSE)
Germination
Secondary metabolite
Tropical Forest tree

ABSTRACT

BACKGROUND AND OBJECTIVES: *Falcataria moluccana* is a potential forest tree species with high economic value in indonesia, and it is widely planted in various forests and landscape restorations. The planting of *F. moluccana* has experienced a decline in productivity attributed to a reduction in site quality and heightened susceptibility to pest and disease infestations. Dark septate endophytes are a group of root endophytic fungi that have potential as biological control and promoter agents. The objective of this study is to evaluate the symbiotic capabilities of various isolates of dark septate endophytes, assess the impact of dark septate endophytes on the sprouting of *F. moluccana* seeds, and identify the secondary metabolites generated as a result of this symbiotic relationship.

METHODS: The study encompassed the employment of three isolates of dark septate endophytes, specifically *Rhizopycnis vagum*, *Curvularia sp.*, and *Dendrothyrium sp*. Those isolates were inoculated on the seeds of *F. moluccana* and observed the endophytism and metabolite compounds produced after 23 hours and 14 days of inoculation time.

FINDINGS: Three new findings of this study were: 1) the dark septate endophytes isolates, i.e., *Rhizopycnis vagum*, *Curvularia sp.*, and *Dendrothyrium sp*. could colonize *F. moluccana* seeds on the surface with a colonization rate of 96 percent, 100 percent, and 32.5 percent, and entered the seed tissue and the sprout roots with a colonization rate of 93.3 percent, 93.3 percent, and 70 percent. The dark septate endophytes colonization could be seen at the beginning of germination, inoculation of 0-23 hours, and after germination until observation at the age of 14 days; 2) The dark septate endophytes has the potential to improve seed germination and vigor of *F. moluccana*, by speeding up the germination process and increasing the vigor index, this condition is expected to produce seeds that can grow and survive environmental stress; 3) The dark septate endophytes has the potential to trigger an increase secondary metabolite compounds in *F. moluccana* seeds, which can be as antibacterial, antifungal, and antioxidants such as the Hexamethyl Cyclotrisilaxane compound, 1-Isopropenyl-4-methyl-1,3-cyclohexadiene, and Acetamide, 2, 2,2-trifluoro-N-methyl-N- (trimethylsilyl) as a form of plant protection when the *F. moluccana* seeds grew and developed to be a normal seedling. These conditions are believed to produce high-quality seedlings that can grow and adapt well to their new environment after being outplanted.

CONCLUSION: Colonization of *F. moluccana* seeds by dark septate endophytes does not have a negative impact on seed viability. Therefore, inoculating seeds with dark septate endophytes can serve as an effective seed treatment method, resulting in the production of robust and healthy *F. moluccana* seedlings. This approach can contribute to enhancing the success of planting efforts aimed at restoring degraded forest and landscape areas.

DOI: 10.22034/gjesm.2024.10.SI.02

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

NUMBER OF REFERENCES
56

NUMBER OF FIGURES
6

NUMBER OF TABLES
2

*Corresponding Author:
Email: *yose011@brin.go.id*
Phone: +6282 3206 84712
ORCID: 0000-0003-1143-3103

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Endophytic microorganisms are defined as those microorganisms that inhabit plant tissues for a portion of their life cycle and are capable of establishing themselves within the host without inducing any disease symptoms (Kumar *et al.*, 2020). Endophytic symbiosis has the potential to produce secondary metabolites that function as antibacterial (Bhardwaj and Agrawal, 2014), antifungal (Chaudhary *et al.*, 2022), fungicide, and antioxidants (Wen *et al.*, 2022), which can suppress disease in plants and increase the tolerance of host plants to biotic and abiotic environmental stress conditions (Sukapiring, 2016). Endophytes have been reported to provide numerous advantages to their host plants, such as promoting plant growth and defending plants against attacks by plant pathogens (Sari, 2020). Endophytes from the fungal group acting as biological control agents include *Acremonium zeae* (Auer and Ludwig-Müller, 2015), *Phomopis cassia* (Tewari *et al.*, 2019), *Periconia* sp., *Ampelomyces* sp., and *Neotyphodium lolii* (Segaran and Sathiavelu, 2019). Dark septate endophytes (DSE) belonging to the group of beneficial endophytic fungi have been identified as potential biological agents. However, their presence has not been extensively documented in comparison to other endophytic fungi, particularly in tropical Indonesia. DSE fungi are root endophytic fungi capable of colonizing plant tissues both intracellularly and intercellularly without causing disease symptoms while stimulating the growth of their host plants, which include agricultural (Surono and Narisawa, 2017) and forestry plants (Marfuah *et al.*, 2023). The precise nature of their symbiotic function remains unclear; however, numerous investigations have demonstrated that DSE plays a significant part in enhancing the ability of host plants to adapt to and withstand biotic (Dalimunthe *et al.*, 2023) and abiotic (Marfuah *et al.*, 2023) stresses. This enables the plants to maintain their health and vitality in comparison to non-symbiotic plants. Within this mutually beneficial partnership, diverse DSE strains have the capability to generate metabolite compounds that serve to shield plants from a range of stress factors (Dalimunthe *et al.*, 2023). One of DSE's unique or distinctive characteristics is that DSE has melanin hyphae and forms microsclerotia in the host plant's root tissues, this is very useful because it makes the host plant tolerant to various stress conditions (Surono and Narisawa, 2018). DSE can suppress the growth of pathogens *Fusarium oxysporum* (Zaffan *et al.*, 2019), and *Ridigoporus microporus* (Dalimunte *et al.*, 2023) with various mechanisms such as parasitism and the production of pathogenic antifungal compounds. DSE can suppress pathogens that cause fusarium wilt in *Lycium barbarum* plants (Chen *et al.*, 2022) and *Asparagus officinalis* (Surono and Narisawa, 2018). The efficacy of DSE in managing pathogen attacks is intricately linked to its symbiotic relationship with the host plant and the precise method of inoculation. Studies on the association of DSE fungi with tropical forest tree species have not been widely reported. A Few forest trees are associated with DSE, including *Jatropha curcas* (Marfuah *et al.*, 2023), *Acacia leucopoea, Albizia* sp., *Lagerstroemia parviflora Roxb, Cassia fistula Linn* (Tripathi, 2014) and *Pinus merkusii* (Akhir *et al.*, 2024) and various pine plants (Chu *et al.*, 2019) in subtropical regions. The potential of endophytes warrants further investigation for their application in the forestry industry, particularly in enhancing the growth of forest trees while addressing the numerous challenges posed by pests and diseases affecting these species. According to Malicka *et al.* (2022), the application of DSE to plants experiencing drought stress can improve the condition of the root system architecture, and physiology, and increase hydraulic properties. The facilitation of plant growth is underpinned by the ease of cultivating DSE, thereby enhancing the potential for DSE to be harnessed in phytoremediation, revegetation, and the restoration of degraded land projects. According to Widyani *et al.*, (2024), DSE has the potential to be a green economic alternative that supports environmental sustainability efforts through the application of seed briquettes. Kumar *et al.* (2018) highlighted that DSE is frequently linked with plant species thriving in challenging environmental settings. The application of DSE fungal inoculation technology holds significant potential for the restoration and reforestation of delicate and degraded forest ecosystems (Pandey *et al.*, 2016). DSE also has the potential to be used in future conservation programs (Pandey *et al.*, 2016). Akhtar *et al.* (2021) suggest that utilizing DSE presents a significant potential for phytoremediation and land reclamation in areas affected by pollution. This will of course also support sustainable agriculture. The use of DSE is essential to be studied, such as in the *Falcataria moluccana* (Miq.) Plant. Barneby and J.W.

Grimes are commonly known as falcata (Mazo *et al.*, 2020). *F. moluccana*, locally known as sengon is one of Indonesia's tropical forest plants with high economic value, especially in Java Island (Rahayu *et al.*, 2021). The growth of the *F. moluccana* tree is presently hindered by a range of pests and diseases. (Nuraeni *et al.*, 2016). Powdery mildew induced by the fungus *Oidium* sp., along with damping-off, caused by various pathogenic fungi such as *Pythium* spp., *Fusarium* spp., *Botryodiplodia* spp., and *Rhizoctonia* spp., as well as tumor rust disease caused by the fungus Uromycladium tepperianum, pose a notable challenge in falcata nurseries (Ryley, 2024). The absence of success in controlling pathogenic fungi in Indonesian *F. moluccana* seedlings, especially using various non-endophytic biological agents, encourages the efforts to use endophytic biological agents. Compared to other biological agents, the advantage of endophytes is their symbiotic potential with host plants so that they do not have to compete in new ecosystems or with microorganisms that have been in the ecosystem for a long time (Perez *et al.*, 2020). The DSE fungus has the potential to be used as a plant endophyte, so it is necessary to study the ability or potential of DSE to colonize *F. moluccana* roots and increase the adaptation and growth of *F. moluccana* which is widely planted in various forest and landscape restoration programs in Indonesia. The present study postulates that DSE fungi, which are acknowledged as endophytic fungi capable of promoting plant growth, may function as endophytes for trees in the forestry industry. DSE would help stimulate growth and protect forestry plants, such as *F. moluccana*, which are extensively cultivated in Indonesia for forest and landscape restoration programs, against both biotic and abiotic stresses. Consequently, additional research is required to confirm the ability and potential of DSE fungi to inhabit the roots of *F. moluccana* and enhance its growth. The aims of the current study were 1) to determine the symbiotic potential of DSE isolates, i.e., *Rhizopycnis vagum* MM12, *Curvularia* sp. PP 2.3, and *Dendrothyrium* sp. CPP 1.1.4 in *F. moluccana* and 2) to determine the effects of DSE on *F. moluccana* seed germination and secondary metabolites produced in those symbiotic interactions. This study was conducted at the Seed Testing Laboratory, Center for Standard and Instrument Implementation of Forestry and Environment, Bogor, and at the Soil Mycology Laboratory, Indonesian Soil Research Institute in Bogor, Indonesia, in 2020.

MATERIALS AND METHODS

Materials

The DSE fungi, i.e., *Rhizopycnis vagum* MM12, *Curvularia* sp. PP 2.3, and *Dendrothyrium* sp. CPP 1.1.4, was used in this study. The DSE fungal isolates were liquid inocula, namely pieces of mycelium in sterile water with a 10^5 hyphae milliliter (mL)/ density. The *F. moluccana* seeds that were used have been stored for five years in an airtight container (in the refrigerator) with a temperature of 2-4 degrees Celsius (°C) and humidity of 40-50 percent (%). The seeds were from community forests in Kediri Regency, East Java, Indonesia (7°55'45.5" S, 112°11'38.3 E).

Inoculation of DSE isolates in F. moluccana seeds

This study has been carried out at the Seed Testing Laboratory, Center for Standard and Instrument Implementation of Forestry and Environment, Bogor, and at the Soil Mycology Laboratory, Indonesian Soil Research Institute in Bogor, Indonesia. The seeds underwent sterilization through immersion in hot distilled water at a temperature ranging from 50 to 90 degrees Celsius, followed by a one-hour cooling period in a glass beaker. The seeds were soaked for 23 hours (h) in each DSE solution as treatment, namely *R. vagum, Curvularia* sp., and *Dendrothyrium* sp. Separately. *F. moluccana* seeds soaked in sterile distilled water were used as a control (ISTA, 2016). This activity was carried out at the Laboratory of the Center for Standard and Instrument Implementation of Forestry and Environment, Bogor, Indonesia.

Observation of DSE colonization on the surface of seeds, seed viability, and seedling growth

The seeds that underwent treatment were germinated on sterile straw paper media and subsequently positioned within a Petri dish measuring 12 cm in diameter. The straw paper sterilization was done in an oven at 103°C for two hours. Germination was carried out in a germinator growth room type IPB 73-2A at a temperature of 24–30°C and a humidity of 90–95%. The experiment involved conducting four repetitions of each treatment, with each repetition utilizing 50 *F. moluccana* seeds. The assessment of DSE colonization in the seeds was determined by calculating the percentage of colonized seeds



Fig. 1: Germination of *Falcataria moluccana* in Petri dishes

in relation to the total number of seeds cultivated on the straw paper medium. This study used four treatments (three DSE and one control), with four replicates, each replicate consisted of 50 seeds. Dark hyphae growth was observed on the surface of the shoots, indicating the colonization of DSE fungi in *F. moluccana* seeds (Fig. 1).

The germination response was used to assess the seed viability, indicating the seeds' capacity to sprout under typical environmental conditions. Seed germination is the percentage of the number of seeds that grow into normal sprouts divided by the number of seeds planted (ISTA, 2016). Observations regarding germination criteria revealed that the sprouts measured twice the length of the seeds (ISTA, 2016). Germination observations were carried out every day until the 14th day after incubation or until no seeds germinated. The calculation of seed germination, using Eq. 1 (ISTA, 2016):

$$\text{Germination percentage (\%)} = \frac{\sum germinated\ seeds}{\sum sowed\ seeds}\ x100\ \% \quad (1)$$

The germination speed was observed every day so that the last day of observation for seeds was normal, using Eq. 2 (Lo Porto *et al*., 2019):

$$\text{Germination speed (\% /day)} = \frac{nihi+n2h2+n3h3+\ldots\ldots\ldots nihi}{n1+n2+n3+\ldots\ldots\ldots\ldots ni} = \frac{\sum nihi}{\sum ni} \quad (2)$$

ni = Number of seeds germinated on day i (item);

hi = The number of days it took to reach the tinier number of sprouts.

The vigor index was obtained by calculating the days it takes to germinate with the number of germinating seeds. The vigor index is calculated using Eq. 3 (Damalas *et al*., 2019):

$$\text{Vigor index} = \frac{G1}{D1} + \frac{G2}{D2} + \frac{G3}{D3} + \ldots\ldots\ldots \frac{Gn}{Dn} \quad (3)$$

G = the number of seeds that germinate on a certain day; D = time corresponding to that amount;

n = The number of days at the last calculation.

Observation of DSE colonization in Falcataria moluccana's radicles (roots)

Root colonization was assessed through the purification and staining of the roots, following a modified procedure Kormanik *et al*. (1980). The number of roots observed for each treatment was 10 roots. The root purification process is soaking the *F. moluccana* root measuring ± 1 cm, in a 10% potassium hydroxide (KOH, Sigma-Aldrich). The submerged roots underwent heating in a water bath set at a temperature of 70°C for a duration of 15 minutes. The roots are rinsed with running water until slimy. The roots were immersed in a 1% hydrochloric acid (HCL, Sigma-Aldrich) solution and heated in a water bath at 70°C for five minutes. The HCl solution was disposed of, and the roots were thoroughly rinsed under running water until they were clean and prepared for the subsequent coloring process. The *F. moluccana* root was stained using 0.01% Fuchsin acid dye, namely 0.1 g of Fuchsin (Sigma Aldrich) dissolved in 1 liter of mixed lactic acid solution (a mixture of 875 ml of lactic acid, 63 ml of glycerol (Merck), and 62 ml

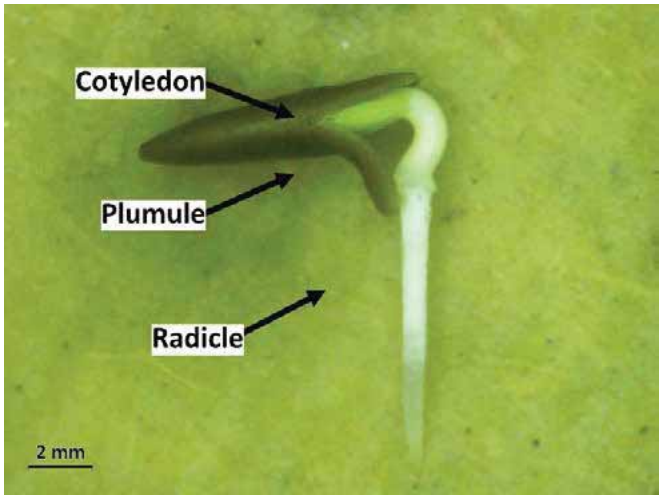


Fig. 2: Sprout structure of *Falcataria moluccana* seed

of ion-free water (Sigma-Aldrich). The *F. moluccana* root pieces were immersed in the lactic acid solution for 24 hours. Observations of DSE colonization were conducted on root segments by positioning the root samples on a glass slide. These preparations were examined microscopically at a magnification of 200 times. The roots-clearing process and the observation of the percentage of colonization in the roots were carried out at the Soil Mycology Laboratory at the Indonesian Soil Research Institute in Bogor, Indonesia. The evaluation of DSE colonization in sprouted roots involved calculating the percentage of colonization within the root shoots (radicles). This calculation was based on the ratio of infected roots exhibiting DSE fungi to the total number of roots observed, 14 days following the incubation of the root sprouts. Another observation response was the observation of the growth of the shoot structure, namely the length of the radicle and plumule (Fig. 2). Each treatment was replicated four times with a total of 10 sprouts in each replication.

Analysis of secondary metabolite compounds

The secondary metabolite compounds generated during the initial germination phase and after 14 days of aging of *F. moluccana* sprouts following inoculation with individual DSE isolates were identified. The secondary metabolite compounds were analyzed using gas chromatography-mass spectrometry (GC-MS). The approach for obtaining bioactive compounds from the seed-inoculated DSE fungal isolate was conducted based on the method described by Waruwu *et al*. (2016). The seed inoculated DSE isolate suspension was filtered gradually using Whatman filter paper No. 1. The suspension was centrifuged at 5,000 rpm for 20 minutes at 4°C. The obtained supernatant was filtered again. The Health Laboratory of the Local Government in Jakarta, Indonesia, utilized GC-MS for qualitative analysis of bioactive compounds. Analysis of bioactive compounds by GC–MS used Agilent Technologies 6890 Gas Chromatograph with AutoSampler and 5975N Mass Selective Detector and Chemstation data system at 70 eV with an HP 5 MS column (30 (m) x 0.25 (mm) I.D x 0.25 micrometer (µm) film thickness). The temperature of the injection port was set at 250oC, while the ion source temperature was maintained at 230oC. Additionally, the interface temperature was set to 280oC, and the quadrupole temperature was controlled at 140°C. The initial temperature at 70°C holds for 2 minutes, rising at 5°C per minute to 150°C hold for 10 minutes, rising at 10°C per minute to 250°C hold for 15 minutes. Helium was the carrier gas at a 0.9 mL per minute flow rate. The interpretation of the GC-MS spectrum involved a comparison with information found in the GC-MS library associated with the National Institute of Standards and Technology (NIST). The sample's peak and its corresponding ion fragment were compared against a database of known compounds, leading to

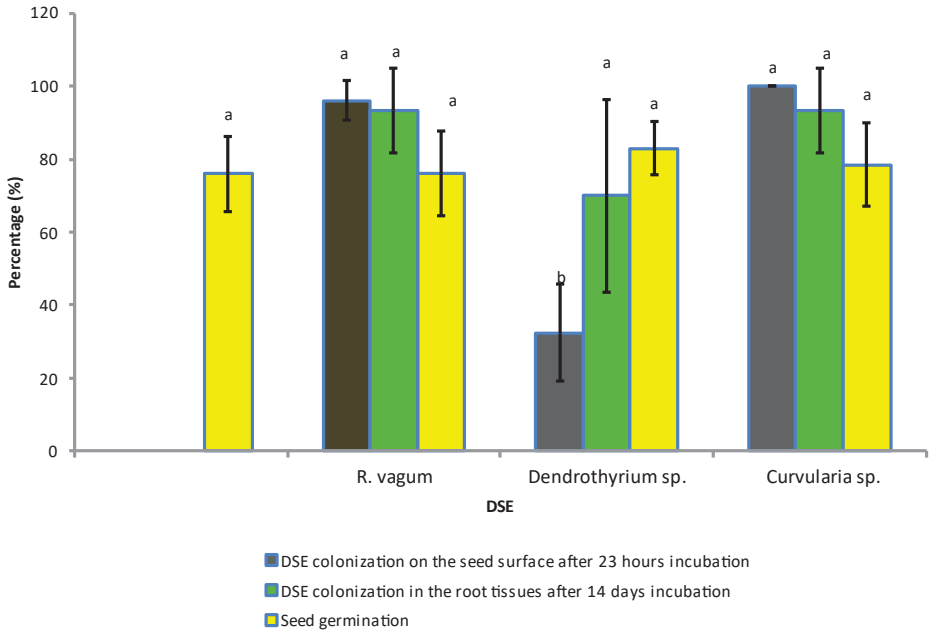


Fig. 3. The percentage of colonization of DSE fungal isolates on the surface of the seeds (after 23 hours incubation) and roots of *F. moluccana* sprouts (after 14 days incubation) and the percentage of germination. Values are means ± standard deviation (SD), total sample size (n) = 4. Means with the same letter were not significantly different (P < 0.05) after Tukey's Honestly Significant Difference test

the determination of the percentage similarity.

Data analysis

Analysis of variance was performed to determine the treatment effects on the percent colonization, germination percentage, germination speed, vigor index, radicle length, plumule, and secondary metabolite analysis. Prior to analysis, the data, which was presented in percentage form, underwent arcsine and square root transformations in order to achieve normalization. Tukey's honestly significant difference test (Tukey's HSD) was conducted to compare the cultivars if they were different for treatments. The Tukey's HSD test was conducted to compare the means across different sources of inoculum, with a significance level set at ($p < 0.05$). Variance analysis used SPSS 16 Software. The neural network analysis result is the data clustering into groups with similar petrophysical properties (classification). The classification was based on the values of the time-averaged shear-wave velocity to a depth of 30 meters (Vs30), and the horizontal-to-vertical spectral ratio (H/V value).

RESULTS AND DISCUSSION

The colonization of DSE isolates on the surface of *F. moluccana* sprouts after 23 hours showed a significant correlation with the use of DSE inoculants ($p < 0.05$). Inoculants *R. vagum* and *Curvularia* sp. (96%; 100%) colonized were higher than *Dendrothyrium* sp. (32.5%) (Fig. 3). The colonization rate of the three DSE fungal isolates in the roots of *F. moluccana* sprouts was relatively consistent, with values ranging from 70.00% to 93.33% (Fig. 3). DSE colonized the seeds were still in good health conditions, and did not appear to show any damage or rot.

There is limited research on the colonization of endophytic fungi in forestry tree seeds or during the germination process. The information about the colonization process of seeds from the beginning of germination until the age of 14 days, especially for *F. moluccana* seeds has not been reported as well as seeds from other plants. The DSE fungus exhibits the capability to inhabit host plant seeds following inoculation and during the germination phase. DSE could colonize both on the surface of the seeds and penetrate the *F. moluccana* seed tissues. *F. moluccana*

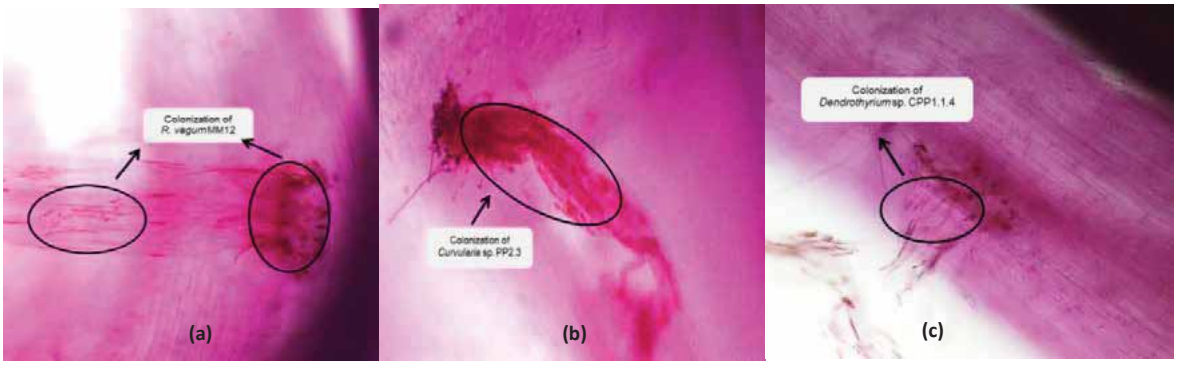


Fig. 4: DSE fungal isolates microscopic colonization of (a) *R. vagum* MM 12; (b) *Curvularia* sp. PP 2.3; and (c) *Dendrothyrium* sp. CPP1.1.4 on the roots of *F. moluccana* seedlings after 14 days of inoculation

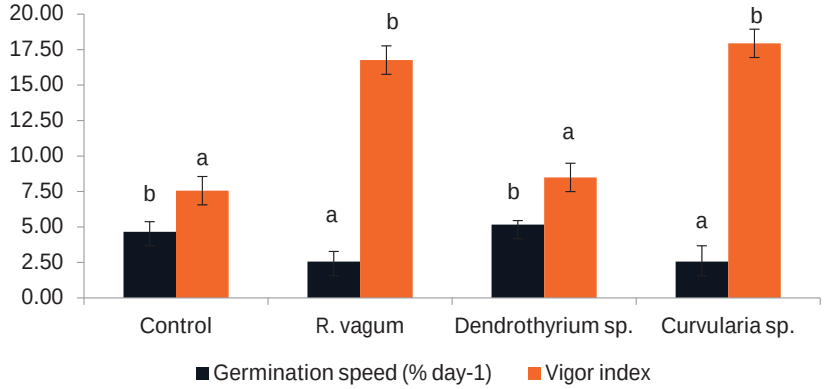


Fig. 5: Germination speed and vigor index of *F. moluccana* seeds on the control and DSE inoculation treatment. Values are means ± SD, n = 4. Means with the same letter were not significantly different ($P < 0.05$) after Tukey's Honestly Significant Difference test.

sprouts inoculated with the DSE fungal species, *R. vagum,* and *Dendrothyrium* sp., showed colonization on the seeds' surface (96% -100%) and in the root sprout's tissue (70.00%-93.33%). The microscopic analysis revealed the colonization of F. moluccana sprout roots by the DSE function, as depicted in Fig. 4. This indicates the ability of the DSE function to form a symbiotic relationship with the roots of *F. moluccana* sprouts. This colonization showed that two DSE fungi have the potency to symbiosis with the *F. moluccana* plant since the beginning of germination. Boddy and Hiscox (2016) stated that if a plant were a suitable host for a fungus, it would colonize more plant tissues. This study presents the initial documentation of the DSE colonization process on *F. moluccana* seeds following a 23-hour seed immersion treatment, as well as the subsequent colonization of seedlings up to 14 days post-inoculation.

The initial mechanism of DSE colonization in *F. moluccana* sprouts was identified by the presence of dark mycelium, specifically melanin, on the plumule. Hyphae may have infected the entire sprout tissue, including the radicle (root candidate), macroscopically the mycelium is not visible on the surface of the radicle. The *F. moluccana* sprouts inoculated by the *Dendrothyrium* sp. exhibited a low colonization rate (32.5%) on the surface of the seeds, while showing a high colonization rate (70%) at the roots. Each of the DSE species tested showed differences in their colonization ability, although the three DSE species colonized the *F. moluccana* seeds at the beginning of the treatment. The efficacy of DSE inoculation in seeds from the point of inoculation to germination is of significant importance as it serves as a protective measure against pathogenic fungi that tend to target seeds during the critical stage of germination. Post hoc test analysis results of the germination speed and vigor index of *F. moluccana* seeds can be seen in Fig. 5.

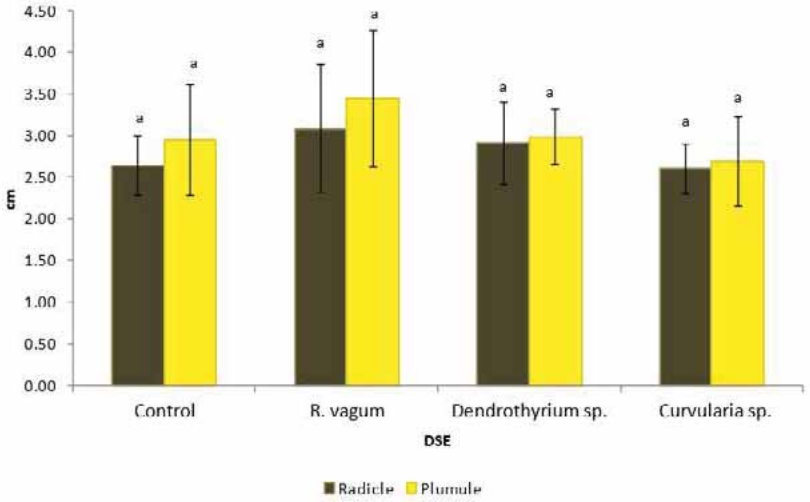


Fig. 6: The radicle and plumule length of *F. moluccana* sprouts aged 14 days after inoculation with DSE and control. Values are means ± SD, n = 4. Means with the same letter were not significantly different (P < 0.05) after Tukey's Honestly Significant Difference test.

The outcomes of the analysis of variance indicated that the introduction of the DSE fungi had no impact on the percentage of *F. moluccana* seed germination (Fig. 3) and the length growth of *F. moluccana* sprouts radicles and plumules (Fig. 6). However, there was a notable difference in germination speed and vigor index (Fig. 5), and no disease symptoms were observed in *F. moluccana* seedlings .*F. moluccana* seeds inoculated with the fungus *Dendrothyrium* sp. and *Curvularia* sp. showed a higher germination percentage than the control (without DSE inoculation). The seed germination rate of *F. moluccana* varies between 76.0% and 83.0%, as illustrated in Fig. 3. Similarly, the development of *F. moluccana* sprouts was influenced by the inoculation of *R. vagum* fungi, which resulted in an increase in the length of both the radicle and plumule compared to the control group; however, this difference was not statistically significant (Fig. 6). The existence of DSE fungi in the *F. moluccana* rooting sprouts does not cause a negative influence based on the performance of germinated seeds. The three DSE isolates successfully colonized the seeds and sprouts of *F. moluccana*, exhibiting no signs of disease. Furthermore, the seeds of *F. moluccana* were able to grow robustly without experiencing any damage rotting. Until the 14th day, the *F. moluccana* sprouts still look fresh and healthy. The germination ability of *F. moluccana* seeds infected with the DSE fungi was relatively high (76% –83%) and did not differ from control (76%). The germination ability is not different from the results of other studies, which are the germination percentage of fresh and healthy seeds of *F. moluccana* ranging from 71% (Mazo *et al*., 2020) to 88% (Istikorini *et al*., 2019). The *R. vagum* and *Curvularia* sp. can accelerate germination, or the time needed for germination is shorter with high vigor than the control (without DSE inoculation). The non-pathogenic (endophytic) fungi *R. vagum, Curvularia* sp*., and Dendrothyrium* sp. have been found to not only be harmless to *F. moluccana* seeds, but also to actively support their growth and development. The germination speed of *F. moluccana* seeds inoculated by *Dendrothyrium* sp. was not significantly different from the control but significantly different from the germination speed of the seeds inoculated by *R. vagum* and *Curvularia* sp. (Fig. 5). The control's vigor index value did not show a significant difference compared to the seeds inoculated by *Dendrothyrium sp*, however, it did exhibit a significant variance when compared to the vigor index value of the seeds inoculated by *R. vagum* and *Curvularia* sp. (Fig. 5). The *F. moluccana* seeds inoculated by *R. vagum* and *Curvularia* sp. germinate faster (2.56 days) than the control (4.6 days), and the *F. moluccana* seeds inoculated by *Dendrothyrium* sp. (5.6 days). Figs. 4 and 5 show the vigor index value of the seeds inoculated by *R. vagum* and *Curvularia* sp. (16.7 and 17.9) were higher than the vigor index

value of the control (7.5) and the seeds inoculated by *Dendrothyrium* sp. (8.5). Seeds exhibiting high vigor demonstrate an enhanced capacity for rapid germination. These results indicated that the *R. vagum* and *Curvularia* sp. application could increase the vigor the seeds germinate faster. It has been observed that DSE fungi, such as *R. vagum* and *Dendrothyrium* sp., possess the capacity to promote the growth of *F. moluccana*, as demonstrated by the growth rate of *F. moluccana* seedlings. There was an increase in radicle and plumule length in seedlings colonized by *R. vagum* and *Dendrothyrium* sp. compared to controls which is 17.11% and 10.27% radicles and 17.0% and 1.36% for plumules. According to Surono and Narisawa (2017), the DSE *Phialocephala fortinii* was found to have a positive impact on the growth of *Asparagus officinalis*. Nevertheless, it is crucial to acknowledge that some isolates of this species may actually hinder growth. DSE fungi isolated from the roots of *Astragalus adsurgens* can increase *Pinus tabulaeformis* seedlings and have the potential to prevent wilting caused by the nematode *Bursaphelenchus xylophilus* (Chu *et al*., 2019). The outcomes of this study suggest that the application of DSE fungi on *F. moluccana* seeds can be considered as a valuable seed treatment approach to boost germination, thereby serving as a fundamental stage in the cultivation of superior quality *F. moluccana* seeds. Endophytic microbe›s mechanism in inducing resistance is by colonizing plant tissue to stimulate plants to increase the production of metabolite compounds in the form of peroxidase enzymes that play a role in plant resistance (Mengistu, 2020). The mechanism of the DSE function in protecting plants against pathogenic attack includes indirect inhibition through the formation of secondary metabolites such as salicylic acid, jasmonic acid, and ethylene. These metabolites function to bolster plant resistance to pathogens or act as antimicrobials, including phytoalexin (Kaur *et al.*, 2022). The identification of secondary metabolite composition plays a vital role in identifying bioactive compounds that act as plant

Table 1: Identification results and levels (%) of *Falcataria moluccana* seed active compounds, without DSE inoculation (control) and with DSE inoculation treatments after 23 hours of inoculation using the GC-MS method

No.	Compound	DSE			
		Control	*R. vagum*	*Curvularia* sp.	*Dendrothyrium* sp.
1	Acetamide, 2,2,2-trifluoro-N-methyl-N-(trimethylsilyl)	-	25.20	26.17	23,33
2	Hexamethyl Cyclotrisilaxane	29.35	-	-	-
3	2,2,4,4,6,6-Hexamethyl-1,3,5,2,4,6-trioxatrisilinane	13.38	-	-	-
4	1-Isopropenyl-4-methyl-1,3-cyclohexadiene	-	43.88	43.06	44.66
5	Acetamide,2,2,2-trifluoro-N-N-bis (trimethylsilyl)	-	2.40	2.32	2.37
6	N-Tetramethyl-N-(trimethylsilyl) silanamine	-	2.56	2.59	2.58
7	2,2,7,7-tetramethyl-3,6-dioxa-2,7-Disilaoctane	-	2.82	2.85	-
8	Ethylene glycol, DI-TMS	-	-	-	2.98
9	Diethyl disulfide	-	1.51	1.60	1.55
10	2.2.4.4.6.6.8.8-Octamethyl-1.3.5.7.2.4.6.8-tetraoxatetrasilocane	24.48	-	-	-
11	1-Butanol.2-iodo-	4.20	-	-	-
12	Tris (trimethylsilyl) amine	-	9.33	9.17	9.68
13	Decamethylcyclopentasiloxane	8.12	-	-	-
14	Silane. trimethyl [(1-propylnonyl)oxy]- atau 4-Trimethylsilyloxydodecane	-	7.54	7.24	-
15	1-Ethyl-1-pentanonyloxyl-1-silacyclopentane	-	-	-	7.66
16	Dodecamethylcyclohexasiloxane	1.70	-	-	-
17	4-hydroxy-2.9-dimethoxy-1.10-oxy-1.10B-[(N-Methyl)Iminoethano]	4.08	-	-	-
18	Hexadecanoic Acid	1.95	-	-	-
19	3-Alpha-Chloro-4-4-dimethyl-3-beta-nitro5.alpha-Cholestane	4.08	-	-	-
20	Acetamide.2-(adamantan-1-yl)-N-[2-(adamantan-1-yloxy)propoyl]-	1.95	-	-	-

Table 2: The active compound identification results of *Falcataria moluccana* seedlings without DSE inoculation (control) and DSE inoculation treatments after 14 days of inoculation using the GC-MS method

No.	Compound	DSE			
		Control	*R. vagum*	*Curvularia* sp.	*Dendrothyrium* sp.
1	Acetamide. 2.2.2-trifluoro-N-methyl-N-(trimethylsilyl)	8.43	9.67	14.18	26.15
2	1-piperidicbecarboxylic acid. 4-(1-methyl propyl)-methyl ester	17.55	-	13.52	-
3	1-Isopropenyl-4-methyl-1.3-cyclohexadiene	44.16	43.53	42.68	43.34
4	Acetamide.2.2.2-trifluoro-N-n-bis (trimethylsilyl)	2.38	-	2.27	2.39
5	Bis (trimethylsilyl) trifluoroacetamide	-	2.28	-	-
6	N-Tetramethyl-N-(trimethylsilyl) silanamine	2.53	2.51	2.45	2.46
7	Bis(trimethylsilyl) carbonate	2.71	2.62	2.62	2.59
8	Diethyl disulfide	1.51	1.53	1.48	1.51
9	Tris (trimethylsilyl) amine	9.13	8.83	8.86	9.26
10	2-Quinazolinamine	-	7.20	-	6.97
11	Isopropyl triethylsilyl ether/ dodecanol	6.43	-	6.92	-

defenses. The identification secondary metabolites present in *F. moluccana* seeds, both in the absence of DSE inoculation (control) and following DSE inoculation (DSE treatments), was performed after a duration of 23 hours. This was achieved by comparing the ion fragments of each sample against the NIST database on GC MS library (Table 1). The major compound in control was hexamethyl cyclo trisiloxane which was identified by appearing at three higher peaks of ion precursor at mass-to-charge ratio (m/z) 207, 208, and 96. Meanwhile, in three different isolates, the major compound was 1-isopropenyl-4-methyl-1,3-cyclohexadiene which also was verified by appearing higher peak at m/z 119, 91, and 134. A diverse array of secondary metabolite compounds was observed in both control and treatment groups following 23 hours of inoculation, indicating a difference in the metabolite compounds produced. Metabolite compounds in control group (seeds that did not receive DSE inoculation) exhibited significant differences compared to those in the DSE treatment group. The compounds in the DSE treatment were almost similar between each isolate; only a few different compounds were produced, such as seeds that were inoculated with *R. vagum* MM12 and *Curvularia* sp. PP2.3 to produce 2,2,7,7-tetramethyl-3,6-dioxa- compounds. 2,7-Disilaoctane and Silane, trimethyl [(1-propylnonyl) oxy] - or 4-Trimethylsilyloxydodecane, while the seeds inoculated with isolate *Dendrothyrium* sp. CPP1.1.4 did not produce either of these compounds. Furthermore, the metabolite compound 1-Ethyl-1-pentanonyloxyl-1-silacyclopentane was exclusively generated by seeds that were inoculated with *Dendrothyrium* sp. CPP 1.1.4.

The metabolite content analysis of *F. moluccana* seedlings after 14 days of inoculation (DSE treatments and control) can be seen in Table 2. As described, the identification of compounds in both the control and DSE treatment was conducted through the utilization of the NIST database. The highest peak from the GC-MS spectrum of control and DSE treatment was the same at retention time 3.507-3.521 with higher ion fragments found at m/z 119, 91, and 134. Referring to the NIST library, this compound was identified as 1-Isopropenyl-4-methyl-1,3-cyclohexadiene. Additionally, this method was employed to identify the potential compound associated with each peak. There are 11 secondary metabolites in the root section of *F. moluccana* sprouts, namely seeds without DSE inoculation (control) and seeds with DSE after 14 days of inoculation. Variations in secondary metabolites were noted in the control treatment post 23 hours of incubation and 14 days after inoculation (Tables 1 and 2). After 14 days of inoculation, seeds treated with control and DSE treatments were both able to produce the same metabolite compounds. Metabolite compounds such as Acetamide, 2,2,2-trifluoro-N-methyl-N- (trimethylsilyl), 1-isopropenyl-4-methyl-1,3-cyclohexadiene, N-Tetramethyl-N-(trimethylsilyl) silanamine, Diethyl disulfide, and Tris (trimethylsilyl) amine (Table 2). Metabolites of 1-piperidicbecarboxylic acid, 4- (1-methyl propyl) -methyl ester, and Isopropyl triethylsilyl ether/

dodecanol were only produced by the seeds that were not inoculated and inoculated with *Curvularia* sp. PP 2.3 (Table 2). The Acetamide, 2,2,2-trifluoro-N-n-bis (trimethylsilyl) metabolite compound was produced by seeds that were not inoculated with DSE, inoculated with *Curvularia* sp. PP2.3 and inoculated with *Dendrothyrium* sp. CPP 1.1.4 (Table 2). Whereas metabolite compounds, such as 2-Quinazolinamine, were exclusively synthesized by seeds inoculated with *R. vagum* MM12 and *Dendrothyrium sp* CPP1.1.4, as these compounds were not generated by seeds that lacked DSE inoculation. The Bis (trimethylsilyl) trifluoroacetamide metabolite compound was only produced by seeds inoculated with *R. vagum* MM12 (Table 2).

During the initial stage of inoculation (23 hours), the predominant metabolite found in the seeds of *F. moluccana* control was Hexamethylcyclotrisilaxane, constituting 29.35% of the total composition. This compound is also reported as the main component of the stem in *Syzygium alternifolim* (Yugandhar and Savithramma, 2017) and is also found in medicinal plants such as *Olea europaea* (Zohdi *et al*., 2023) and *Bauhinia acuminate* (Krishna *et al*., 2015). Hexamethylcyclotrisiloxane is a secondary metabolite that can withstand the entry of bacteria (antibacterial) (Nurain *et al*., 2017). Other compounds that also tend to be the main compounds are 2, 2, 4, 4, 6, 6, 8, 8-Octamethyl-1,3,5,7,2,4,6,8- tetraoxatetra silocane compounds (24,48%) which are antimicrobial (Krishna *et al.,* 2015). After 14 days of germination, the two secondary metabolites were not detected. Secondary metabolite compounds that are relatively low in *F. moluccana* seeds without DSE inoculation (control) are Hexadecanoic Acid (Palmitic Acid) (1.95%) which acts as an antifungal (El-Sheekh *et al*., 2022), and antimicrobial (Krishnaveni *et al*., 2014). The findings suggest that the seeds of *F. moluccana* possess inherent antifungal and antimicrobial compounds. Several research results stated that the content of secondary metabolite compounds from the *F. moluccana* plant came from the flavonoid, saponin, tannin, terpenes, and alkaloid groups (Rumidatul *et al.*, 2021). Differences in secondary metabolite synthesis are evident among distinct parts of the same plant species. The leaves of *F. moluccana* contain alkaloids, potential to produce natural antioxidants (Rumidatul *et al*., 2021), while the stem contains flavonoids, saponins, phenolic hydroquinones, tannins, triterpenoids, and steroids but does not contain alkaloids. The analysis conducted by Rahmawati *et al*. (2019) demonstrated the existence of alkaloids, tannins, flavonoids, saponins, steroids, anthraquinone, and triterpenoids in the extract obtained from *F. moluccana* sawdust. Alkaloid secondary metabolite compounds can be found in both seeds and fruit (Abegaz *et al.,* 2019). The alkaloids can protect the plant from pests, act as plant boosters, and act as hormone regulators. Rahmawati *et al*. (2019) reported Triterpenoids and steroids in the stems of *F. moluccana* make the plants that were resistant to tumor rust. Even these results were reported by Rahmawati *et al*., (2019), who reported that *F. moluccana* trees resistant to tumor rust contained higher levels of flavonoids, saponins, triterpenoids, and steroids than susceptible trees. The flavonoid group is involved in various processes including safeguarding against ultraviolet radiation, contributing to pigmentation, and enhancing resistance to diseases. The GC-MS analysis showed that the inoculation process and the interaction between the *F. moluccana* seeds and the DSE fungi tested produced secondary metabolites that were very different from those of the control, especially at the beginning or during the 23 hours of the inoculation process. After the introduction of *R. vagum*, *Curvularia* sp., and *Dendrothyrium* sp., a number of secondary metabolites were exclusively generated in *F. moluccana* seeds. Those secondary metabolites are Acetamide compound, 2,2,2-trifluoro-N-methyl-N-(trimethylsilyl); 1-Isopropenyl-4-methyl-1,3-cyclohexadiene; Acetamide, 2,2,2-trifluoro-N-N-bis (trimethylsilyl); N-Tetramethyl-N- (trimethylsilyl) silanamine; Diethyl disulfide; and Tris (trimethylsilyl) amine. The majority of these substances are TMS derivatives that serve as antifungal (Nurain *et al*., 2017) and antibacterial functions (Abdel-Aziz *et al*., 2019). Meanwhile, The secondary metabolites produced by the seeds that were not inoculated by DSE (control) were Hexamethyl Cyclotrisilaxane; 2,2,4,4,6,6,8,8-Octamethyl-1,3,5,7,2,4,6,8-tetraoxa tetrasilocanel; 1-Butanol, 2-iodo; Decamethylcyclopenta siloxane; Dodecamethylcyclo hexasiloxane; 4-hydroxy-2,9-dimethoxy-1,10-oxy-1,10B- [(N-Methyl) Iminoethano]; Hexadecanoic Acid; 3-Alpha-Chloro-4-4-dimethyl-3-beta-nitro5. alpha-Cholestane; Acetamide, 2- (adamantan-1-yl) -N- [2- (adamantan-1-yloxy) propoyl]. Hexamethyl

Cyclotrisilaxane is an antibacterial compound, and the Hexadecanoic Acid compound is antifungal; this means that the seeds of *F. moluccana* already contain secondary metabolites that can withstand the entry of microbes (bacteria or fungi). Following 14 days of germination (Table 2), variations in the secondary metabolites generated in the control seeds were observed, which were absent at the initial stage (23 hours inoculation). The metabolic compounds are Acetamide, 2,2,2-trifluoro-N-methyl-N-(trimethylsilyl); N-Tetramethyl-N- (trimethylsilyl) silanamine; Tris (trimethylsilyl) amine; Bis (trimethylsilyl) carbonate; Diethyl disulfide, and 1-Isopropenyl-4-methyl-1,3-cyclohexadiene. The production of six secondary metabolites was observed in seeds inoculated with DSE as early as 23 hours post-inoculation. This indicates the ability of the DSE species (*R. vagum, Curvularia* sp., and *Dendrothyrium* sp.) to spur the formation of metabolite compounds more quickly for defense in the seeds or sprouts of *F. moluccana* as a form of adaptation to environmental conditions, all of which function as antibacterial and antifungal. *Dendrothyrium* sp., at the beginning of inoculation (23 hours), produced ethylene glycol, Trimethylsilyl (DI-TMS), and 1-Ethyl-1-pentanonyloxyl-1-silacyclopentane, which were not produced by seeds inoculated by *R. vagum*, *Curvularia* sp., and control). DI-TMS, an ethylene glycol compound, exhibits antibacterial properties according to Moghayedi *et al*. (2017). Similarly, Cadophora sp. also demonstrates antibacterial activity (Tan *et al*., 2018). The 1-Ethyl-1-pentanonyloxyl-1-silacyclopentane compound is responsible for the pharmacological activity of antioxidants, antimicrobials, and antifungals (Arumugam *et al*., 2018). Secondary metabolite compounds with a high percentage on the 14th day after DSE inoculated seeds are 1-Isopropenyl-4-methyl-1,3-cyclohexadiene (42.68%–43.53%), this compound can function as an antifungal (Wibawa *et al*., 2019), and Acetamide, 2,2,2-trifluoro-N-methyl-N- (trimethylsilyl) (9.67%–26.15%), which is a flavonoid group and can be an antimicrobial compound (Nurain *et al*., 2017). On the 14th day of observation, 1-Isopropenyl-4-methyl-1,3-cyclohexadiene and Acetamide, 2,2,2-trifluoro-N-methyl-N- (trimethylsilyl) were also found in lower percentages in control *F. moluccana* seeds. The potential of DSE leads to an enhancement in the production of secondary metabolite compounds within *F. moluccana* seeds, which may exhibit antimicrobial and antifungal characteristics, serving as a mechanism for plant defense. DSE's ability to trigger an increase in secondary metabolites related to disease resistance in plants certainly influences the percentage increase in plant life. This results have a substantial influence on the effectiveness of forest reforestation and rehabilitation programs, ultimately contributing to environmental sustainability. The research conducted by Spagnoletti *et al*. (2020) supports the notion that DSE can play a crucial role in combating plant infections caused by pathogens, enhancing nutrient uptake in the soil, and minimizing the negative consequences of challenging environmental conditions, ultimately fostering the growth and well-being of plants in adverse environments. This is also supported by Spagnoletti *et al.* (2020) research, which summarized the specific response of DSE which is one of the efforts to increase plant tolerance to climate change. Adinugroho *et al*. (2024) demonstrated that the utilization of indigenous tree species in rehabilitation endeavors leads to promising results in carbon sequestration, emphasizing the essential requirement for well-growth plant species. In this study, the inoculation of DSE on *F. moluccana* has a beneficial impact on promoting plant growth. The findings of this study suggest that the observed effect is linked to the synthesis of metabolite compounds by DSE, which not only promote growth but also offer protection against various biotic and abiotic stressors. This study is the first report of symbiotic interaction between DSE and *F. moluccana*, specifically focusing on the seed-to-seedling stage. The results of this study contribute additional insigjt regarding the significant impact of DSE in supporting growth from seed development seedling stage. According to Lin *et al.* (2023), DSE can also be used in *Cinnamomum kanehirae* conservation because it can increase seedling height, fresh weight, and chlorophyll concentrations. The findings suggest that DSE has the potential to promote the development of *F. moluccana* seeds, despite the fact that the DSE strains utilized originated from rice and chili plant tissues rather than the intended plant species. This finding supports the claims made by other studies on DSE, which indicate that numerous selected DSE strains can establish a symbiotic relationship not only with

their original host plant but also with a diverse range of other plants. According to Yinli *et al*. (2023), DSE can help *Morus alba* to increase soil carbon and nitrogen absorption. It also can increase plant height, crown size, and root and leaf biomass of *M. alba*. Furthermore, DSE has the potential to enhance carbon sequestration. Utilizing DSE in leaf applications may prove beneficial in the ecological rehabilitation of mining sites, serving as a means to introduce novel microbial fertilizers that aid in restoration efforts and the recovery of former mining lands (Yinli *et al*., 2023). According to Yinli *et al*. (2023), DSE and the metabolites produced can increase the growth of *Medicago sativa* L. plants, affecting photosynthesis. In the future, this can be used in green microbial fertilizer development as a means of ecological restoration in mining areas.

CONCLUSION

This study reports for the first time that DSE could colonize the *F. moluccana* (economic value tree, widely planted for forest and landscape restoration in Indonesia) seed at the initial inoculation and germination period and produce compounds that function as antioxidants and antimicrobial pathogens. During the initial stages of germination, *F. moluccana* seeds may be colonized by the DSE species *Rhizopycnis vagum*, *Curvularia* sp., and *Dendrothyrium* sp. Inoculation can occur within the first 23 hours after germination, and colonization may continue up to 14 days post-inoculation. The DSE isolates (*R. vagum*, *Curvularia* sp., and *Dendrothyrium* sp.) could colonize seeds on the surface with a colonization rate of 96%, 100, and 32.5%, and entered the seed tissue and the sprout roots with a colonization rate of 93.3%, 93.3%, and 70%. DSE colonization on the *F. moluccana* seeds did not significantly affect the percentage of seed germination, although there was a tendency for the germination percentage of the seeds infected with the DSE fungus to be relatively high (76%–83%) compared to the control (76%). The seeds of *F. moluccana* that were inoculated with *R. vagum* and *Curvularia* sp. exhibited a quicker germination process, taking only 2.56 days compared to the control group which took 4.6 days. On the other hand, the seeds of *F. moluccana* that were inoculated with *Dendrothyrium* sp. took 5.6 days to germinate. The vigor index value of the seeds inoculated by *R. vagum* and *Curvularia* sp. (16.7 and 17.9) was higher than the vigor index value of the control (7.5) and the seeds inoculated by *Dendrothyrium* sp. (8.5). Seeds with high vigor will be able to germinate faster, indicated that the application of the *R. vagum* and *Curvularia* sp. could increase the vigor so that the seeds germinate faster. The presence of DSE fungi has been shown to enhance the production of secondary metabolites in *F. moluccana* seeds, which include various antibacterial, antifungal, and antioxidant compounds such as the Hexamethyl Cyclotrisilaxane compound, 1-Isopropenyl-4-methyl-1,3-cyclohexadiene, and Acetamide, 2, 2,2-trifluoro-N-methyl-N-(trimethylsilyl). DSE fungi, *R. vagum, Curvularia* sp., and *Dendrothyrium* sp., can stimulate the formation of metabolite compounds more quickly for defense in *F. moluccana* seeds or sprouts as a form of adaptation to environmental conditions, all of which function as antibacterial and antifungal. By adhering to this condition, *F. moluccana* seeds and seedlings are able to thrive and exhibit increased vitality in their growth process. DSE inoculation, that were inoculated by *R. vagum*, was able to increase growth which was characterized by faster growth of radicle and plumule length. The accelerated development of radicles and plumules in seedlings will result in the production of seeds that generate "target seedlings" more rapidly, which are defined as normal seedlings prepared for out-planting. The colonization of the seed by DSE enables the establishment of a seed defense system against both abiotic (environmental) and biotic (pest and disease) stress conditions. DSE inoculation on *F. moluccana* seeds can be used as a seed treatment and can produce healthy and vigor seedlings, thereby increasing the success of *F. moluccana* planting in the context of forest and landscape restoration.

AUTHOR CONTRIBUTIONS

S. Surono 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. Y. Yulianti contributed to this work by conceptualizing the study, applying for funding, designing the experimental work, analyzing the data, writing the initial manuscript, and reviewing and finalizing the manuscript. K.P. Putri contributed to this work by conceptualizing the study, designing the experimental work, analyzing the data, writing the initial manuscript, and finalizing the manuscript. D.J.

Sudrajat contributed to this work by conceptualizing the study, designing the experimental work, analyzing the data, and supporting and finalizing the manuscript. Y.M.M.A. Nugraheni contributed to performing experiments, analyzing the data, and supporting manuscript writing and corresponding author duties. C. Sriherwanto contributed to supporting the manuscript writing, reviewing, and revising. M.A. Syabana contributed to performing experiments, analyzing the data, and supporting manuscript writing. N. Widyani contributed to analyzing the data and supporting manuscript writing. N. Yuniarti contributed to analyzing the data and supporting manuscript writing. M. Zanzibar contributed to analyzing the data and supporting manuscript writing. E. Rustam contributed to analyzing the data and supporting the manuscript writing. R.U.D. Sianturi contributed to analyzing the data, supporting manuscript writing, and finalizing the manuscript.

ACKNOWLEDGMENT

This study, including data analysis and drafting, was supported by Riset Inovasi Indonesia Maju (RIIM) 4th, with funding provided by LPDP (Ministry of Finance, Republic of Indonesia), contract numbers: [B-3838/II.7.5/FR.06.00/11/2023, B-4259/III.5/FR.06.01/11/2023]. Authors extend the gratitude to Dr. Syamsul Falah from the Department of Biochemistry, IPB University, for the valuable suggestions and input. Authors also thank all those who have helped and supported 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

©2024 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
µL	Microliter
µm	Micrometer
^{0}C	Degree Celcius
cm	Centimeter
D	The time corresponding to that amount
DSE	Dark septate endophytes
DSE CPP.1.1.4	*Dendrothyrium* sp. CPP 1.1.4
DSE PP2.3	*Curvularia* sp. PP 2.3
DSE MM12	*Rhizopycnis vagum* MM12
DI-TMS	Trimethylsilyl (or double TMS)
Eq.	Equation
et al.	And others
H	Hours
hi	The number of days it took to reach the smaller number of sprouts
HCL	Hydrochloric acid
i.e.	Id est (that is)
IPB	*Bogor Agricultural University*
ISTA	International Seed Testing Association
G	The number of seeds that germinate on a certain day
g	Gram

GC-MS	Gas chromatography-mass spectrometry
H/V	The horizontal-to-vertical spectral ratiO
Kg	Kilogram
Km	Kilometer
KOH	Potassium hydroxide
m	Meter
mm	Millimetre
mL	Milliliter
mm	Millimeter
m/z	mass-to-charge ratio
N	total sample size
N	Number of total samples or the number of days at the last calculation
ni	Number of seeds germinated on day i
NIST	National Institute Standard Technology
p <0.05	P value **<**0.05
Rpm	Revolutions per minute
SD	Standard deviation
sp.	Species
spp.	Several species
SPSS	Statistical Package for the Social Sciences
Tukey's HSD	Tukey's honestly significant difference test
Vs30	The time-averaged shear-wave velocity to a depth of 30 meters
TMS	Trimethylsilyl

REFERENCES

Akhir, J.; Herliyana, E.N.; Surono; Budi, S.W., (2024). The first report of dark septate endophytes from Indonesian *Pinus merkusii* and its symbiosis role as a plant growth promoter in nursery condition. Biodiversitas. 25(1): 312-321 **(10 pages).**

Akhtar, N.; Wani, A.K.; Dhanjal, D.S.; Mukherjee, S., (2022). Insights into the beneficial roles of dark septate endophytes in plants under challenging environment: Resilience to biotic and abiotic stresses. World J. Microbiol. Biotechnol., 38(5): 79 (**14 pages**).

Abdel-Aziz, M.S.; Hathout, A.S.; El-Neleety, A.A.; Hamed, A.A.; Sabry, B.A.; Aly, S.E.; Abdel-Wahhab, M.A., (2019). Molecular identification of actinomycetes with antimicrobial, antioxidant, and anticancer properties. Comunicata Sci., 10(2): 218-231 (**14 pages**).

Abegaz, B.M.; Kinfe, H.H., (2019). Secondary metabolites, their structural diversity, bioactivity, and ecological functions: An overview. Phys. Sci. Rev., 4(6): 20180100 **(30 pages)**.

Adinugroho, W.C.; Tata, H.L.; Lisnawati, Y.; Nuroniah, H.S.; Dewi, R.; Heriansyah, I., (2024). Land use changes, green house gas emissions, and rehabilitation model of native tree species towards sustainable management. Global J. Environ. Sci. Manage., 10(3): 1249-1274 (**26 pages**).

Arumugam, T.; Kumar, P.S.; Hemavathy, R.V.; Swetha, V.; Sri, R.K., (2018). Isolation, structure elucidation, and anticancer activity from *Brevibacillus brevis* EGS 9 that combats multi-drug resistant actinobacteria. Micro. Pathogenesis. 115:146-153 (**8 pages**).

Auer, S.; Ludwig-Müller, J., (2015). Biological control of clubroot (*Plasmodiophora brassicae*) by the endophytic fungus Acremonium alternatum. J. Endocytobiosis Cell Res., 26, 43-49. (**7 pages**).

Ayala, S.; Thomas, V.; Nelson, G.; Soti, P. (2023). Soil conditions regulate the patterns of root colonization by fungal endophytes in Guinea grass (*Megathyrsus maximus*). Symbiosis. 91(1): 101-105 (**5 pages**).

Boddy, L.; Hiscox, J. (2016). Fungal ecology: principles and mechanisms of colonization and competition by saprotrophic fungi. Microbiol. Spectr., 4(6): 10-1128 (**16 pages**).

Bhardwaj, A.; Agrawal, P., (2014). A review fungal endophytes: as a storehouse of bioactive compound. World J. Pharm. Pharmacol. Sci., 3:228-237 (**10 pages**).

Chaudhary, P.; Agri, U.; Chaudhary, A.; Kumar, A.; Kumar, G., (2022). Endophytes and their potential in biotic stress management and crop production. Front. Microbiol., 13: 933017. (**22 pages**).

Chen, S.; Tao, Z.; Baosen, J.; Juan, D.; Siyuan, Y.; Peiwen, G., (2022). Study on antibacterial activity of dark septate endophytes against *Fusarium oxysporum* in Chinese wolfberry. Acta Hortic. Sinica. 49(7): 1519-1531. (**13 pages**).

Chu, H.; Tang, M.; Wang, H.; Wang, C., (2018). Pinewood nematode infection alters root mycoflora of *Pinus tabulaeformis* Carr. J. Appl. Microbiol., 125:554–563 (**10 pages**).

Chu, H.; Wang, H.; Zhang, Y.; Li, Z.; Wang, C.; Dai, D.; Tang, M., (2021). Inoculation with ectomycorrhizal fungi and dark septate endophytes contributes to the resistance of *Pinus* spp. to pine wilt disease. Front. Microbiol., 12: 687304. (**15 pages**).

Dalimunthe, CI.; Soekarno, B.P.W.; Munif, A.; Surono, (2019). Selection and potential test of dark septate endophytes fungus as biological agent of white root rot disease (*Rigidoporus microporus*) on the rubber plant. Indonesian J. Nat. Rubb. Res., 37(1):11 – 20 (**10 pages**).

Damalas, C.A.; Koutroubas, S.D.; Fotiadis, S. (2019). Hydro-priming effects on seed germination and field performance of faba bean in spring sowing. Agric. 9(9): 201 (**11 pages**).

Dipali Majumder, D.M.; Binalata Kangjam, B.K.; Devi, K.J.; Domesticity Lyngdoh, D.L.; Janshame Tariang, J.T.; Dwipendra Thakuria, D.T.; Aakash Goyal, A.G. (2016). Endophytes: an emerging microbial tool for plant disease management. In The handbook of microbial bioresources. Wallingford UK. 179-192 (**14 pages**).

Hidayat, I. (2019). Dark septate endophytes and their role in enhancing plant resistance to abiotic and biotic stresses. Plant growth promoting rhizobacteria for sustainable stress management. Springer. 35-63 (**29 pages**).

ISTA, (2016). International Rules for Seed Testing, ISTA Basserdorf. International Seed Testing Association. **(46 pages).**

Istikorini, Y.; Wulandari, A.S.; Sari, O.Y., (2019). Fungi associated with *Falcataria moluccana* (L.) seed. IOP Conf. Series: Eart and Environ. Sci. 468. 012052 (**7 pages**).

Kaur, S.; Samota, M.K.; Choudhary, M.; Choudhary, M.; Pandey, A. K.; Sharma, A.; Thakur, J., (2022). How do plants defend themselves against pathogens-Biochemical mechanisms and genetic interventions. Physiol. Mol. Biol. Plants. 28(2): 485-504 (**20 pages**).

Krishna, A.S.R.; Hafza, S.; Chandrika, P.G.; Priya, L.C.; Rao, B.K.V., (2015). Pharmacological properties, phytochemical and GC-MS analysis of *Bauhinia acuminata* Linn. J Chem. Pharm. Res., 7(4):372-380 (**9 pages**).

Krishnaveni, M.; Dhanalakshmi, R.; Nandhini, N., (2014). GC-MS analysis of phytochemicals, fatty acid profile, antimicrobial activity of Gossypium seeds. Int. J. Pharm. Sci. Rev. Res., 27(1): 273-276 (**4 pages**).

Kumar, A.; Prasad, M.N.; Maiti, S.K.; Favas, P.J., (2018). Mycoremediation for mine site rehabilitation. In Bio-geotechnologies for mine site rehabilitation (pp. 233-260). Elsevier., (**28 pages**).

Kumar, A.; Droby, S.; Singh, V.K.; Singh, S.K.; White, J. F., (2020). Entry, colonization, and distribution of endophytic microorganisms in plants. Microb. Endophytes. 1-33 (**33 pages**).

Lo Porto, C.L.; Sergio, L.; Boari, F.; Logrieco, A.F.; Cantore, V., (2019). Cold plasma pretreatment improves the germination of wild asparagus (*Asparagus acutifolius* L.) seeds. Sci. Hortic., 256, 108554: 1-6 (**6 pages**).

Lin, L. C., Chen, H.Y., Lin, W.R. (2023). Fostering growth in *Cinnamomum kanehirae* cuttings: the beneficial role of dark septate endophytes in forest nursery management. Forests. 15(1), 16 (**12 pages**).

Malicka, M.; Magurno, F.; Piotrowska-Seget, Z., (2022). Plant association with dark septate endophytes: When the going gets tough (and stressful), the tough fungi get going. Chemosphere. 302, 134830 (**8 pages**).

Marfuah, D. S.; Hamim, H.; Sulistyaningsih, Y. C.; Surono, S.; Setyaningsih, L.; Saprudin, D., (2023). Dark septate endophyte inoculation improved Pb phytoremediation of *Jatropha curcas* and *Reutealis trisperma* on gold mine tailings. Biorem. J., 1-18 (**18 pages**).

Mazo, K.R.F.; Jawani, R.M.; Tambac, C.S., (2020). Germination potential of Falcataria mollucana (Miq.) Barneby & J.W. Grimes on different hot water pre-germination treatment and germination media. Int. J Biol. Sci., 17(1): 183-187 (**5 pages**).

Mengistu, A.A., (2020). Endophytes: colonization, behaviour, and their role in defense mechanism. Int. J. Microbiol., 1: 6927219 (**8 pages**).

Moghayedi, M.; Ahmadzadeh, H.; Ghazvini, K.; Goharshadi, E.K., (2017). Neglected antibacterial activity of ethylene glycol as a common solvent. J. Microb. Pathogen., 107:457-461 (**5 pages**).

Nurain, I.O.; Clement, O.; Bewaji; Jarrett, S.; Johnson; Robertson, D.; Davenport; Zhang, Y., (2016). Potential of three ethnomedicinal plants as antisickling agents. Mol. Pharm., 4(1): 172-182 (**11 pages**).

Pandey, R.R.; Chongtham, I.; Muthukumar, T., (2016). Influence of season and edaphic factors on endorhizal fungal associations in subtropical plantation forest trees of Northeastern India. Flora. Morphol. Distrib. Funct. Ecol. Plants., 222: 1-12 (**12 pages**).

Pérez, L.I.; Gundel, P.E.; Zabalgogeazcoa, I.; Omacini, M., (2020). An ecological framework for understanding the roles of Epichloë endophytes on plant defenses against fungal diseases. Fungal Biol. Rev., 34(3): 115-125 (**11 pages**).

Rahayu, S.; Triyogo, A.; Widyastuti, S.M.; Ardianyah, F., (2021). Pests and diseases on Falcataria moluccana trees in agroforestry systems with pineapple in East Java, Indonesia. J. Biol. Divers., 22(5) (**10 pages**).

Rahmawati, D.; Khumaida, N.; Siregar, U.J., (2019). Morphological and phytochemical characterization of susceptible and resistant sengon (*Falcataria moluccana*) trees to gall rust disease. J.Biol. Divers., 20(3): 907-913 (**7 pages**).

Rumidatul, A.; Rahmawati, N.; Sunarya, S., (2021). Production of secondary metabolites and its antibacterial and antioxidant activity during the growth period of endophytic fungi isolated from gall rust sengon plants. Pharmacogn. J., 13(2):1-7 (**7 pages**).

Ryley, M.J., (2024). Wattle gall—the quintessential Australian plant disease. Hist. Rec. Aust. Sci., 35(2): 116-129 (**14 pages**).

Sari, N., (2020) Review of endophytic fungi as biocontrol agents against plant pathogen. Gontor Agro Sci J., 6(1): 55-73 (**19 pages**).

Segaran, G.; Sathiavelu, M., (2019). Fungal endophytes: A potent biocontrol agent and a bioactive metabolites reservoir. Biocatal. Agric. Biotechnol., 21: 101284 (**17 pages**).

Spagnoletti, F.N.; Giacometti, R., (2020). Dark septate endophytic fungi (DSE) response to global change and soil contamination. in: Hasanuzzaman, M. (eds) Plant ecophysiology and Adaptation under climate change: Mechanisms Perspectives II. Springer, Singapore. 629-642 **(13 pages**).

Sukapiring, D.N.; Soekarno, B.P.W.; Yuliani, T.S., (2016). The potency of Secondary metabolic of pepper endophytic fungi as inhibitor agents against seed-borne pathogenic *Fusarium* sp. in vitro. J. Fitopatologi Ind., 12(1): 1–8 (**8 pages**).

Surono; Narisawa, K., (2017). The dark septate endophytic fungus *Phialocephala fortinii* is a potential decomposer of soil organic compounds and a promoter of *Asparagus officinalis* growth. Fungal Ecol., 28: 1–10 (**10 pages**).

Surono; Narisawa, K., (2018). The inhibitory role of dark septate endophytic fungus Phialocephala fortinii against Fusarium disease on the *Asparagus officinalis* growth in organic source conditions. Biol. Control., 121: 159-167 (**9 pages**).

Tan, D.S.Y.; Impas, M.G.W.; Camacho, D.H.; Palisoc, S.T., (2018). Paper-based electrode using Cladophora cellulose-polyaniline composite for electrochemical quantification of toxic lead (II). Cellul. Chem. Technol., 52(9-10): 853-861 (**9 pages**).

Tewari, S.; Shrivas, V.L.; Hariprasad, P.; Sharma, S., (2019). Harnessing endophytes as biocontrol agents. In: Ansari, R., Mahmood, I. (eds) Plant Health Biotic Stress. Springer, Singapore. 2: 189-218 (**200 pages**).

Tripathi, P., (2014). VAM and dark septate endophytic fungi in a tropical dry deciduous forest of central india. Int. Q. J. Life Sci., 1(1): 12-17 (**6 pages**).

Waruwu, A.A.S.; Soekarno, B.P.W.; Munif, A., (2016). Metabolite of endophytic fungi isolated from rice as an alternative to control seed-borne pathogenic fungi on rice. J. Fitopatologi Ind., 12(2): 53–61 (**9 pages**).

Wen, J.; Okyere, S.K.; Wang, S.; Wang, J.; Xie, L.; Ran, Y.; Hu, Y., (2022). Endophytic fungi: an effective alternative source of

plant-derived bioactive compounds for pharmacological studies. J. Fungi., 8(2): 205. (**45 pages**).

Widyani, N.; Sudrajat, D.J.; Rustam, E.; Putri, K.P.; Yuskianti, V., (2024). Direct seeding of *Ceiba pentandra* and *Leucaena leucocephala* using seed briquette with AMF and DSE inoculations to support a green economy. IOP Conf. Ser.: Earth Sci., 012027 (**8 pages**).

Yugandhar, P.; Savithramma, N., (2017). Spectroscopic and chromatographic exploration of different phytochemical and mineral contents from *Syzygium alternifolim* (Wt.) Walp. an endemic, endangered medicinal tree taxon. J. Appl. Pharm. Sci., 7(01):073-085 (**13 pages**).

Yinli, B.I.; Zhuoyou, W.A.N.G.; Zengming, K.E., (2023). Effect of foliar application of DSE fungal solution on growth of *Morus alba* and its prospects of ecological restoration application. Coal Geol. Explor., 51(2), 14 (**9 pages**).

Yinli, B.I., Song, Y., Bai, X., Wang, S. (2023). DSE and its metabolites on *Medicago sativa* L. growth promotion and its potential for ecological restoration in mining areas. Coal Sci. Technol., 51(12), 90-99 (**10 pages**).

Zaffan, Z.R.; Soekarno, B.P.W.; Munif, A.; Surono, (2019). Potential of Indonesia's indigenous dark septate endophytic fungi to control Fusarium Wilt in vitro. In: Fernandez JC, Wibowo C (eds), Proc. of Seameo Biotrop Third Intternational Conference. (**6 pages**).

Zohdi, R.M.; Adli, M.A., Mohsin, H.F.; Mokhtar, S.M.; Low, A.L.M.; Junaidi, A.H.A.; Jahrudin, D.H.J., (2023). GC-MS analysis and antibacterial activity of ethanolic and water extracts of Malaysian *Heterotrigona itama* propolis against selected human pathogenic bacteria. Malays. Appl. Biol., 52(2): 77-84 (**8 pages**).

AUTHOR (S) BIOSKETCHES

Surono, Ph.D., Junior Researcher, Research Center for Applied Microbiology, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *suro004@brin.go.id*
- ORCID: 0000-0003-2526-3491
- Web of Science ResearcherID: NA
- Scopus Author ID: 57194166602
- Homepage: https://www.brin.go.id/

Yulianti, Ph.D., Professor, Senior Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *yuli055@brin.go.id*
- ORCID: 0000-0002-4650-9983
- Web of Science ResearcherID: NA
- Scopus Author ID: 57126207100
- Homepage: https://www.brin.go.id/

Putri, K.P., Ph.D. Candidate, Middle Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *kurn027@brin.go.id*
- ORCID: 0009-0008-0413-4686
- Web of Science ResearcherID: NA
- Scopus Author ID: 56038899100
- Homepage: https://www.brin.go.id/

Sudrajat, D.J., Ph.D., Senior Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *dede036@brin.go.id*
- ORCID: 0000-0002-8256-8454
- Web of Science ResearcherID: NA
- Scopus Author ID: 56590048000
- Homepage: https://www.brin.go.id/

Nugraheni, Y.M.M.A., M.Si., Junior Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *yose011@brin.go.id*
- ORCID: 0000-0003-1143-3103
- Web of Science ResearcherID: NA
- Scopus Author ID: 57211188606
- Homepage: https://www.brin.go.id/

Sriherwanto, C., Junior Researcher, Research Center for Applied Microbiology, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *catu001@brin.go.id*
- ORCID: 0000-0002-5393-6983
- Web of Science ResearcherID: NA
- Scopus Author ID: 57217729443
- Homepage: https://www.brin.go.id/

AUTHOR (S) BIOSKETCHES

Syabana, M.A., Lecturer at the Department of Agricultural Science and Center of Excellence for Local Food Innovation, Sultan Ageng Tirtayasa University, Serang, Indonesia. Jalan Raya Palka Km 3 Panancangan, Kecamatan Cipocok Jaya, Kota Serang, Provinsi Banten 42124, Indonesia.
- Email: *anasyabana@untirta.ac.id*
- ORCID: 0000-0002-8700-5466
- Web of Science ResearcherID: NA
- Scopus Author ID: 57193522315
- Homepage: https://icefory.untirta.ac.id/

Widyani, N., Ph.D. Candidate, Junior Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *nuri013@brin.go.id*
- ORCID: 0000-0003-4465-3292
- Web of Science ResearcherID: NA
- Scopus Author ID: 55917124900
- Homepage: https://www.brin.go.id/

Yuniarti, N., M.Ling., Senior Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *nani017@brin.go.id*
- ORCID: 0000-0002-7536-4664
- Web of Science ResearcherID: NA
- Scopus Author ID: 57205103375
- Homepage: https://www.brin.go.id/

Zanzibar, M., M.M., Senior Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *muha297@brin.go.id*
- ORCID: 0009-0007-5629-6663
- Web of Science ResearcherID: NA
- Scopus Author ID: 57218843173
- Homepage: https://www.brin.go.id/

Rustam, E., Ph.D. Candidate, Middle Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *evay002@brin.go.id*
- ORCID: 0000-0003-0589-0092
- Web of Science ResearcherID: NA
- Scopus Author ID: 57208838148
- Homepage: https://www.brin.go.id/

Sianturi, R.U.D., Ph.D. Candidate, Junior Researcher, Research Centre of Applied Botany, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jalan Raya Jakarta-Bogor KM 46, Cibinong, Jawa Barat, 16911 Indonesia.
- Email: *ratn018@brin.go.id*
- ORCID: 0009-0001-9874-5152
- Web of Science ResearcherID: NA
- Scopus Author ID: 57361686800
- Homepage: https://www.brin.go.id/

HOW TO CITE THIS ARTICLE

Surono; Yulianti; Putri, K.P.; Sudrajat, D.J.; Nugraheni Y.M.M.A.; Sriherwanto, C.; Syabana, M.A.; Widyani, N.; Yuniarti, N.; Zanzibar, M.; Rustam, E.; Sianturi, R.U.D., (2024). Dark septate endophytes symbiosis in Falcataria moluccana and its potency for forest and landscape restoration. Global J. Environ. Sci. Manage., 10(SI): 19-36.

DOI: 10.22034/gjesm.2024.10.SI.02

URL: https://www.gjesm.net/article_714682.html

Global J. Environ. Sci. Manage. 10(SI): 37-52, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH PAPER

The role of nutrient availability and resorption efficiency and their impact on nutrient conservation in mangroves

M.E.B. Gerona-Daga[1,2], R.A. MacKenzie[3], L.G. Sumabat-Dacones[1], C.F.P. Naputo[4], S.G. Salmo III[1,*]

[1] *Institute of Biology, College of Science, University of the Philippines Diliman, Quezon City, Philippines*

[2] *Division of Natural Sciences and Mathematics, University of the Philippines Tacloban College, Tacloban City, Philippines*

[3] *United States Department of Agriculture, Forest Service, Koror, Palau, USA*

[4] *Institute of Environmental Science and Meteorology, University of the Philippines Diliman, Quezon City, Philippines*

ARTICLE INFO

Article History:
Received 03 May 2024
Revised 11 June 2024
Accepted 14 August 2024

Keywords:
Leaf nitrogen and phosphorus
Naturally recolonized ponds
Philippine mangroves
Resorption efficiency
Restoration
Soil nutrients

ABSTRACT

BACKGROUND AND OBJECTIVES: Nutrient availability influences mangrove forest structure and productivity. The conversion of mangroves into aquaculture ponds can lead to significant disturbances, resulting in long-term consequences associated with the clearing of vegetation and changes in the physico-chemical properties of the soil. These alterations may subsequently restrict the availability of essential nutrients, including nitrogen and phosphorus. Consequently, nutrient limitations can constrain mangrove growth and development. Conventional indicators of nutrient limitation are founded on the analysis of leaf nutrient and nutrient resorption ratios, drawing from datasets collected in terrestrial and temperate forest environments. However, these indices may not be applicable to mangroves due to the prevalence of a wide range of environmental settings and occurrences of disturbances. In the Philippines, mangrove ecosystems are represented by diverse stand types, including natural or intact mangroves, restored or planted mangroves, and recolonized stands, which are naturally revegetated abandoned ponds. These different stand types are perceived to have different levels of nutrient availability and resorption capabilities. This study aims to investigate the changes in soil and leaf nutrient concentrations of nitrogen and phosphorus, leaf nitrogen to phosphorus ratio, nitrogen and phosphorus resorption efficiencies, and nitrogen resorption efficiency to phosphorus resorption efficiency ratio across a chronosequence of restored and recolonized stands (with intact natural stands as reference sites) in Ormoc Bay, Philippines.

METHODS: Soil and leaf samples were obtained from both seedlings and mature trees across each vegetation plot in restored, recolonized, and natural stands, totaling 30 plots. Soil (total nitrogen and available phosphorus) and leaf (total nitrogen and total phosphorus) samples were analyzed for nutrient concentrations. The calculations were performed to determine the leaf nitrogen to phosphorus ratio, nitrogen resorption efficiency, phosphorus resorption efficiency, and the ratio of nitrogen resorption efficiency to phosphorus resorption efficiency based on the nutrient concentrations.

FINDINGS: While there was a marked difference in the nutrient composition of soil and leaves across various stand types, the data did not indicate any clear age-related patterns in the restored and recolonized stands. Soil nutrients were not correlated with leaf nutrients suggesting that soil nutrient availability does not necessarily translate to nutrient absorption and accumulation in the leaves. Nitrogen resorption efficiency is similar across stand types. Phosphorus resorption efficiency was highest (76 percent) in recolonized stands suggesting that phosphorus resorption is an adaptive strategy to meet phosphorus demand. Conventional indices of leaf nitrogen to phosphorus and nitrogen resorption efficiency to phosphorus resorption efficiency ratios as indicators of nutrient limitations (as used in other terrestrial systems) may not be applicable in disturbed mangroves because of apparent long-term impacts on soil nutrients following pond construction, operation, and abandonment. Recolonized stands exhibited high phosphorus resorption resulting in low phosphorus concentration of senescent leaves and consequently, low phosphorus input of senescent leaves to soil phosphorus pool.

CONCLUSION: This study demonstrated variations in soil nitrogen and phosphorus, leaf nitrogen and phosphorus, leaf nitrogen and phosphorus ratio, and nutrient resorption efficiencies of nitrogen and phosphorus across stand types and ages. Conventional indices for nutrient limitation of nitrogen and phosphorus using leaf nitrogen to phosphorus and nitrogen resorption efficiency to phosphorus resorption efficiency ratios showed inconsistent indicator of nutrient limitations in mangroves. Hence, a mangrove-specific leaf nitrogen to phosphorus ratio and nitrogen resorption efficiency to phosphorus resorption efficiency ratio are suggested as a more appropriate indicator of nutrient limitation.

DOI: 10.22034/gjesm.2024.10.SI.03

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

NUMBER OF REFERENCES
60

NUMBER OF FIGURES
5

NUMBER OF TABLES
2

*Corresponding Author:
Email: *sgsalmo@up.edu.ph*
Phone: +(632)981-3727
ORCID: 0000-0001-6807-4397

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Nutrient availability (NA) is one of the major factors influencing mangrove forest structure and productivity (Almahasheer *et al.*, 2018). But NA is extremely low in mangrove soils (Kammann *et al.*, 2022). Nitrogen (N) and phosphorus (P) are the primary nutrients often reported to limit mangrove growth (Wei *et al.*, 2023). However, NA varies greatly in mangroves due to soil properties (Adame *et al.*, 2018), tidal inundation, sporadic natural disturbances (Salmo, 2021), and land-use changes (Salvaña *et al.*, 2024). Aquaculture serves as the leading cause of mangrove degradation in Southeast Asia (Contessa *et al.*, 2023). In the Philippines for example, approximately 1,409 hectares (ha) of mangroves were converted to aquaculture ponds from 2000-2020 (Baloloy *et al.*, 2023). The prolonged practice of unsustainable aquaculture has resulted in the neglect and abandonment of numerous ponds (Luo *et al.*, 2022). Abandoned ponds are often highly disturbed environments (Xiong *et al.*, 2021) because of poor soil conditions (e.g., soil excavation, vegetation clearing, and changes in hydroperiod (Salas-Rabaza *et al.*, 2024). The availability of N and P is adversely influenced by these factors, which in turn hampers the growth and development of mangrove seedlings (Chen *et al.*, 2024). Nutrient limitation occurs when the availability of a specific nutrient limits plant growth and productivity (Shi *et al.*, 2024). In natural mangrove stands that are considered to be "nutrient limited", nutrient conservation mechanisms such as nutrient resorption are expected to occur as an adaptation mechanism (Naidoo, 2016). Nutrient resorption refers to a mechanism by which plants conserve nutrients, facilitating the transfer of these essential elements from senescent leaves to other parts of the plant. Globally, terrestrial plants have wide variations in both nitrogen resorption efficiency (NRE), mean at 50 percent (%) and phosphorus resorption efficiency (PRE), mean at 52% (Aerts and Chapin, 1999). But in mangroves (e.g., *Avicennia marina*), NRE and PRE varied widely at 19%-71% and 31%-72%, respectively (Almahasheer *et al.*, 2018). Conventional methods for assessing nutrient limitation typically use terrestrial-based indices, such as the leaf nitrogen: phosphorus (N:P) ratio (Güsewell, 2004) and NRE:PRE ratio (Du *et al.*, 2020). Nevertheless, these indices might not be appropriate for mangrove ecosystems, which are subject to a diverse array of environmental conditions and disturbances. In 2021, the United Nations initiated the Decade of Ecosystem Restoration, aiming to rehabilitate 350 million ha of degraded ecosystems by 2030 (United Nation General Assembly, 2019). Most nutrient-related studies evaluating the benefits of mangrove restoration have focused on carbon accumulation (Ariyanto and Pringgenies, 2024) but rarely assessed changes in NA (Silva *et al.*, 2024). Although there are some studies on NA and resorption efficiencies on mangroves, these are limited to natural stands (Shi *et al.*, 2024; Almahasheer *et al.*, 2018) but rarely account nutrients in restored and recolonized stands. Analyzing nutrient dynamics and contrasting these among natural, restored, and recolonized mangrove stands is crucial for evaluating the stability and recovery of these ecosystems. Classic successional models suggest that mangroves are steady-state ecosystems (Lugo, 1980), but due to periodic disturbance-recovery cycle, it is also considered a successional ecosystem (Odum 1969) with profound cohorts of ages (referred to as "chronosequence" (Jimenez and Lugo, 1985). Studies on the chronosequence of restored planted stands, referred to as "RES" stands, indicates that over time, the structural characteristics of the vegetation can come to closely resemble those of natural forests (Wang'ondu et *al.*, 2014). As mangrove forests mature, increases in soil carbon (Bourgeois *et al.*, 2024) and nutrients are commonly observed (Adame *et al.*, 2018). In recolonized stands (hereon, "COL" stands), where mangroves naturally grow in abandoned ponds, nutrient recovery may be possible through the restoration of tidal flows. The dynamics of tidal flows enable the movement of sediments and nutrients into the ponds, which is essential for the ongoing recovery of mangrove forests (Sidik *et al.*, 2021). Although there is some knowledge regarding the interplay between forest structure, age, and nutrient dynamics in natural mangrove ecosystems, research focusing on the chronosequence of restored and recolonized ponds remains relatively scarce. Understanding nutrient dynamics in restored and recolonized mangroves is fundamentally dependent on this knowledge. This study provides insights on the varying nutrient status and nutrient conservation strategies by investigating changes in soil and leaf N and P, leaf N:P ratio, NRE, PRE, and NRE: PRE ratio across a chronosequence of RES and COL stands (with NAT stands as reference

sites). The hypothesis posits that 1) the levels of nutrients in both soil and leaves are expected to rise with the age of the stand, attributed to enhanced vegetation and soil quality, and 2) nitrogen resorption efficiency (NRE) and phosphorus resorption efficiency (PRE) are anticipated to be greater in restored and recolonized stands compared to natural stands. These values were then compared with intact natural mangroves (hereon, "NAT" stands) as the reference system. This study aims to investigate the changes in soil and leaf nutrient concentrations of nitrogen and phosphorus, leaf N:P ratio, nitrogen and phosphorus resorption efficiencies, and nitrogen resorption efficiency:phosphorus resorption efficiency ratio across a chronosequence of restored and recolonized stands. Fieldworks were carried out in the mangrove forest of Ormoc Bay, mid-eastern Philippines in 2022 to 2023.

MATERIALS AND METHODS

Site information

The mangrove forest in Ormoc Bay is a mixture of restored 'planted' (RES), recolonized abandoned ponds (COL), and natural/intact (NAT) stands receiving sediment and freshwater inputs from Bao River (Fig. 1). RES stands (approximately 5-, 8-, and 30-year [y] old, hereon as R5, R8, and R30) are dominated by *A. marina* species except for the 15-y stands (R15) that are dominated by *Sonneratia alba*. COL stands (approximately 5-, 12-, and 20-y old, hereon as C5, C12, and C20) are naturally recolonized with mixed species of mangroves. Waterways (C5) and dikes either intact (C12) or partially-destructed (C20) were observed in COL stands (Table 1). Ormoc climate is characterized by temporal rainfall variabilities which peaks in December and can reach up to 580 millimeters (mm) (Corporal-Lodangco and Leslie, 2017).

Mangrove soils and leaves collection

To determine soil organic carbon (SOC) and nutrients, soil cores were sampled using an open-faced auger (6.5 centimeters [cm] diameter) at 10 cm depth. At each designated plot, two adjacent cores were collected during low tide to assess 1) soil organic carbon (SOC) levels and 2) concentrations of soil

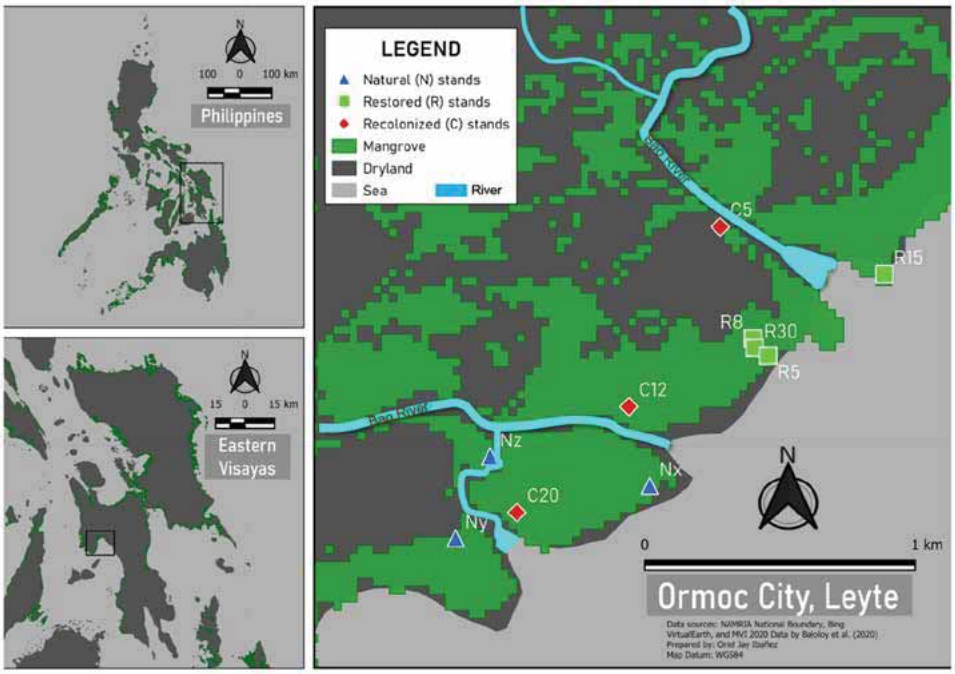


Fig. 1: Geographic location of the study area in Ormoc, Leyte, Philippines
Natural stands (blue triangle), Restored stands (green squares), and Recolonized stands (red diamond). Nx (seaward), Ny (midward), Nz (landward) are natural stands; R5 (5 y old), R8 (8 y old), R15 (15 y old), and R30 (30 y old) are restored stands; C5 (5 y old), C12 (12 y old), and C20 (20 y old) are recolonized stands

Table 1: Vegetation and substrate conditions across stand types and ages in Ormoc mangroves

Parameter	Restored				Recolonized			Natural
	R5	R8	R15	R30	C5	C12	C20	Nx-z
	SW	LW	SW	MW	LW	SW	MW	SW-LW
Vegetation								
Dominant species	*A. marina*	*A. marina*	*S. alba*	*A. marina*	Mixed species			Mixed species
Tree density (ind/ha)	2,249	5,178	1,537	1,732	2,249	4,413	2,858	2,533
Basal area (m^2/ha)	23.75	27.77	18.74	27.69	12.27	17.41	20.02	13.99
Diversity (H')	0.90	0.29	0.90	0.54	1.03	0.19	0.68	1.302
Evenness (E)	0.56	0.21	0.65	0.34	0.64	0.28	0.33	0.51
Dominance (D)	0.47	0.86	0.48	0.75	0.45	0.91	0.73	0.47
Porewater quality								
Salinity (ppt)	28.58±0.25	31.70±1.26	25.86±0.15	28.98±0.67	25.01±0.15	28.54±1.74	29.48±0.29	26.79±1.87
Temperature (°C)	28.80±0.10	29.05±0.11	28.83±0.26	28.68±0.11	28.93±0.26	28.42±0.75	29.38±0.12	29.79±0.45
Redox potential (mV)	-60±05.04	-251.33±21.74	-125.00±09.00	-177.66±33.89	-114.00±15.72	-38.20±6.73	-184.00±15.72	20.03±5.82
pH	5.99±0.29	6.88±0.02	6.43±0.46	6.43±0.46	7.44±0.70	7.45±0.41	6.76±0.03	6.92±0.38

Note: R5 (5 y old), R8 (8 y old), R15 (15 y old), and R30 (30 y old) are restored 'planted' stands; C5 (5 y old), C12 (12 y old) and C20 (20 y old) are naturally recolonized stands. Nx-z are natural stands of unknown ages. SW (seaward), MW (midward), and LW (landward). Based on tidal positions, SW is located at the intertidal zone where mangroves are daily submerged to seawater. MW is located between SW and LW zones. LW is located inland which is approximately 1 kilometer (km) from the shoreline. Porewater quality parameters were measured from each plot using Horiba (U-51, Essex UK)

nutrients. The determination of SOC was conducted using the loss on ignition (LOI) technique (Howard **et al.,** 2014). Each sample was air-dried, oven-dried at 60 degrees Celsius (°C) for 24-48 hours: h (to remove moisture content), and then ignited at 450°C for 4 h (using Neytech Vulcan® muffle furnace). LOI (%) was converted to SOC (%), and corrected for carbonate content by acidification with 1 normality (N) of hydrochloric acid (HCl, J.T.Baker®). Soil samples intended for nutrient analysis were subjected to air-drying for approximately 5 to 7 days, subsequently homogenized, and then finely ground utilizing an agate mortar. Powdered soil samples were forwarded to the Regional Soils Laboratory (Tacloban City, Philippines) for the analyses of total nitrogen (as soil nitrogen [SN]; Dumas-Dry Combustion method (FAO, 2021a), and available phosphorus (as soil phosphorus [SP]; Bray I method (FAO, 2021b). In order to assess leaf nutrient concentrations, samples were gathered from the two predominant mangrove species present in each stand for subsequent nutrient analyses. Around 10-15 leaves from seedlings (hereon as "young leaves") were hand-picked from the first fully expanded leaf after the apical bud. Mature green leaves (hereon as "mature leaves"), devoid of any insect damage or physical injuries, were picked from the 2nd - 3rd internode of the branch from trees, beginning from where the shoots arise. Yellowish senescent leaves (hereon as "senescent leaves") with a well-developed abscission layer (Lovelock **et al.,** 2004) were collected from trees. The young leaves (YNG), mature leaves (MAT), and senescent (SEN) leaves from the triplicate plots were combined to form a composite sample for each leaf stage per stand. Leaf samples were air-dried, oven-dried at 60 °C, then ground to powder. Leaf samples in powdered form were sent to the Central Analytical Services Laboratory located in Baybay City, Philippines, for the determination of total leaf nitrogen (LN) using the Kjeldahl method and leaf phosphorus (LP) concentrations through the vanadomolybdate method, in accordance with the procedures outlined by Motsara and Roy (2008).

Data analysis

Soil nitrogen: phosphorus (Soil N:P) ratio and leaf nitrogen:phosphorus (Leaf N:P) were calculated using mass-based concentrations (Shi *et al.,* 2024). The calculation of NRE and PRE was performed by determining the ratio of the difference in nutrient concentration between mature leaves and senescent leaves, with the results expressed as a percentage (Lovelock *et al*., 2004). Data were tested for normality and homogeneity of variance using the Shapiro–Wilk and Levene's tests. All data were untransformed except for SP values which were log-transformed to conform with the normality test. Data uncertainty was expressed as means ± SEM. One-way analysis of variance (ANOVA) was used to determine differences in soil and leaf nutrient concentrations, leaf N: P, and resorption efficiencies across stand types and ages. Comparison of means was performed with Tukey-HSD post hoc pairwise tests. The data collected from the three natural mangrove stands were pooled since there was no statistically significant difference among stands. Data analysis and visualization were performed using R version 4.2.2 and RStudio version 2023.06.0+421.

RESULTS AND DISCUSSION

Variations of soil nutrients and organic carbon across stand types and ages

SN and SP significantly varied across stand types, ages, and zones within stand types (Fig. 2a-c), $p < 0.05$). RES (0.15±0.01%) and COL (0.18±0.01%) stands have 4% and 27% higher SN than NAT stands (0.14±0.01%; $F = 6.42$, $p < 0.05$), (Fig. 2a). Younger RES (R15: 0.08±0.03%) and COL stands (C5: 0.13±0.01%) had 43% to 7% lower SN than the NAT stands (0.14±0.01%; $p = 0.001$). The SP in RES (8.97±0.74 milligram per kilogram [mg/kg]) and COL (7.05±0.70 mg/kg) stands were 19% and 36% significantly lower than NAT stands (11.10±0.84 mg/kg), (Fig. 2d-f). SP decreased with stand age in RES stands (range: 12.20±1.69 - 6.18 mg/kg), while no distinct pattern was observed in COL stands. SN and SOC values increased from seaward (SW) to landward (LW) in RES stands while SP decreased from SW to LW in COL stands.

The SN (0.16%) and SP (3.58 mg/kg) in COL stands (Fig. 2a-f) were higher than the mean soil nutrient concentrations from natural mangroves in Southeast Asia (range SN:0.02-0.05%; SP: 0.02-25.73 mg/kg), (Table 2). But the SNs (RES: 0.15%, COL: 0.18%, NAT: 0.14%), (Fig. 2a) were higher than those of heavily disturbed mangrove stands (with active shrimp ponds) such as in Todos Santos Bay, Brazil (0.04-0.06%) (Loiola *et al.,* 2023) and planted stands (7-y) in Carey Island, Malaysia (0.04%), (Bakrin Sofawi *et*

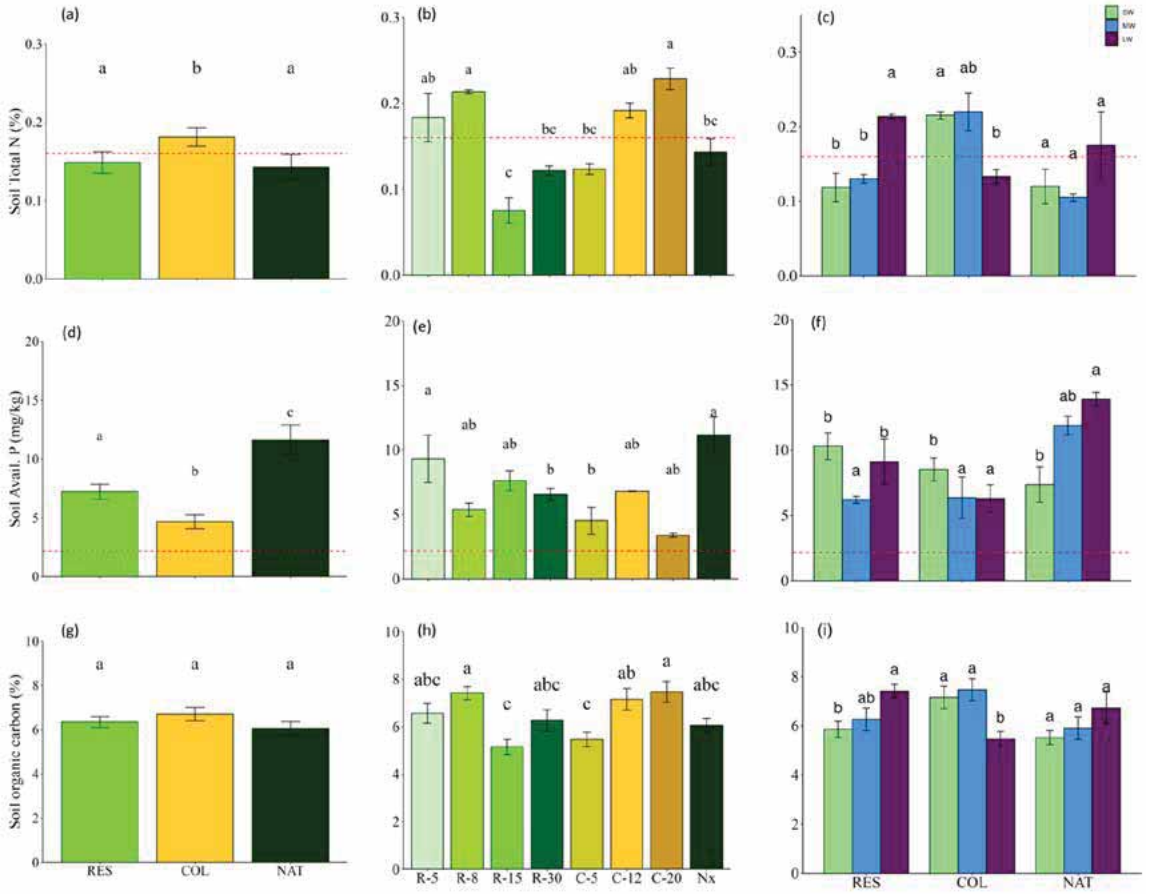


Fig. 2: Soil nitrogen (SN; a-c), available phosphorus (SP; d-f), and soil organic carbon (SOC; g-i) concentrations according to stand types (a,d,g), stand ages (b,e,h), and zonation (c,f,i). Red dashed lines indicate mean SN (0.16%) and SP (3.58 mg/kg) values from natural mangroves in Southeast Asia

al., 2017). In this study, the SPs (RES: 8.97 mg/kg, COL: 7.05 mg/kg, NAT: 11.10 mg/kg), (Fig. 2d) were much lower than the planted (17-, 18-, 50-y) stands in Pangasinan and Bohol, Philippines (mean: 21.56 mg/kg), (Salmo *et al.,* 2013) and active aquaculture ponds in Songkla, Thailand (11.68-102.90 mg/kg (Towatana *et al.,* 2002). The chronosequences of both RES and COL stands did not exhibit a clear SP pattern (Fig. 2d-e). SN concentrations from COL stands increased with stand age, but no distinct pattern was observed from RES stands. Plants absorb essential nutrients from the soil, which are vital for their growth and the synthesis of organic matter. Subsequently, this organic matter is returned to the soil as a result of the decomposition of litter (Sun *et al.,* 2023). In mangroves ecosystems, significant contributions of phosphorus (P) arise from various sources, including litterfall, the mineralization of soil, and human activities such as sewage discharge, agricultural practices, and aquaculture operations (Singh *et al.,* 2015). But because COL stands were once active aquaculture ponds that underwent vegetation clearing (Salvaña *et al.,* 2024), the source of SP is limited. The removal of vegetation, although it allowed for early to mid-vegetation regrowth following the abandonment of the pond, ultimately resulted in a detrimental long-term impact on the soil P pool. The recovery of fauna, especially crabs, plays a significant role in nutrient cycling by facilitating bioturbation processes (Bandibas and Hilomen, 2016). Crab burrowing can alter soil's redox conditions, promoting soil aeration, and N and P availability (Silva *et al.,* 2024). In degraded karst landscapes, an

Table 2: Soil total nitrogen (%) and available phosphorus (mg/kg) from natural mangroves across Southeast Asia

Location	Genus/ species	Soil total nitrogen (%)	Soil available phosphorus (mg/kg)	Sources
Tamsui, Taiwan	*Kandelia candel*	0.2	0.48	Kao and Chang, 1998
		0.13	0.26	
		0.05	1.04	
East Java, Indonesia	-		0.041	Pradipta *et al.,* 2021
			0.027	
			0.032	
			0.039	
			0.043	
			0.032	
			0.038	
			0.021	
			0.029	
			0.032	
			0.038	
Carey Is., Malaysia	*Rhizophora mucronata*	0.027	-	Bakrin Sofawi *et al.,* 2017
Bali, Indonesia	-	0.19	-	Sidik *et al.,* 2019
Pangasinan and Bohol, Philippines	Mixed species	0.18	24.86	Salmo *et al.,* 2013
Trat Province, Thailand	-	-	2.48	Hongwiset *et al.,* 2021
		-	5.96	
Average		0.16	2.17	

improved soil structure and soil nutrients content (C and N) facilitated rapid vegetation succession (Wei *et al.,* 2023; Lu *et al.,* 2022). However, in the semiarid region of China's Loess Plateau, 20 y of afforestation significantly decreased organic carbon and N decomposition rates (Kong *et al.,* 2022). The success of mangrove restoration, akin to that of terrestrial ecosystems, is influenced by multiple factors such as the chronosequence, the techniques employed in restoration, and the unique conditions of the site (Hu *et al.,* 2024). The contrasting nutrient patterns obtained in this study imply the need for more studies to improve the understanding of nutrient dynamics especially in mangroves undergoing recovery.

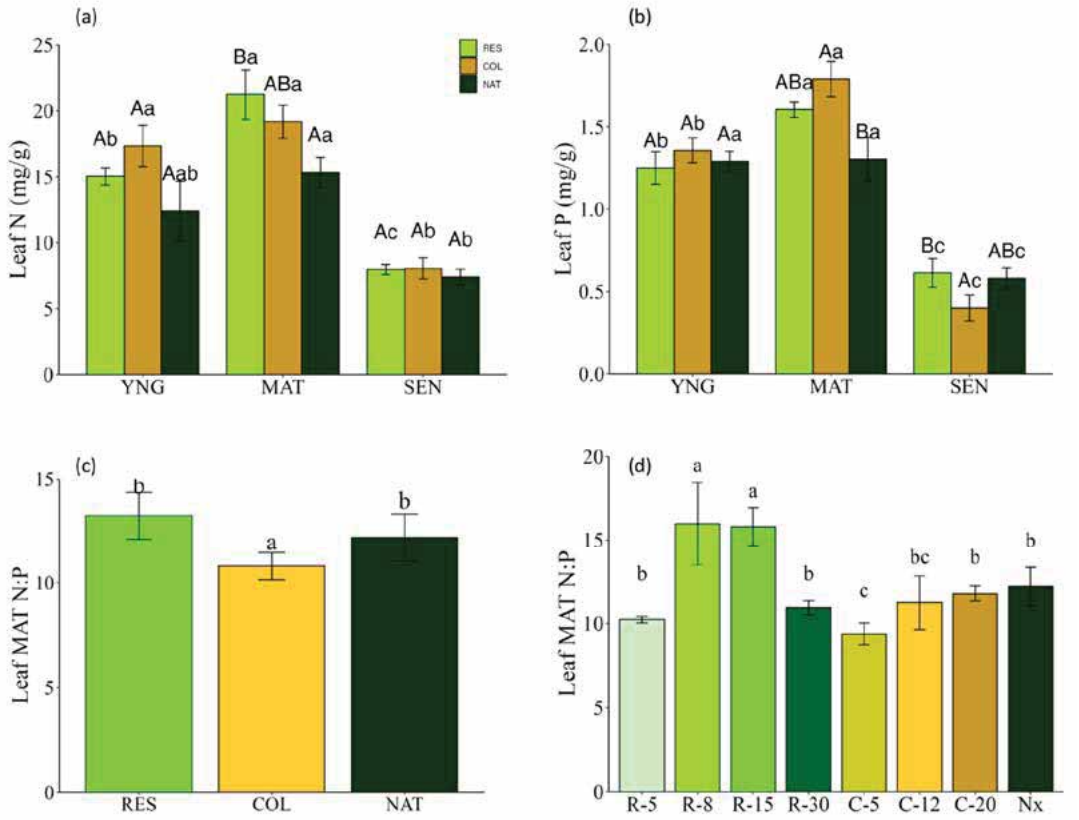


Fig. 3: Leaf N (a) and P concentrations (b) of different leaf stages from different stand types
Leaf N:P ratio of mature leaves according to (c) stand types and (d) stand ages. (a-b) Different capital letters indicate significant differences across stand types of the same leaf stage and lower-case letters represent significant differences between leaf stages at the same stand type (c-d). Different letters indicate significant difference between stand types and stand ages (at α = 0.05; Tukey's HSD test). Young leaves (YNG), mature leaves (MAT), senescent leaves (SEN).

Variations in leaf nitrogen–phosphorus ratios and nutrient resorption efficiencies

The LN and LP concentrations of mature leaves exhibited significant variation among different stand types ($p < 0.05$), (Fig. 3a-b), whereas no such differences were observed in young and senescent leaves. Leaf N: P of mature leaves significantly varied between COL and NAT stands, but not between RES and NAT stands (Fig. 3c). Leaf N:P was relatively stable in different ages in COL stands, but significantly varied among RES stands (Fig. 3d). Mature leaves from RES (21.24±1.87 mg/kg) and COL (20.61±1.24 mg/kg) stands have 39% and 34% higher LN than NAT stands (15.32±1.13 mg/kg; $F = 3.9$, $p = 0.043$), (Fig. 3a). LN and LP significantly increased from young to mature stage, then decreased at senescent stage in all stand types ($p < 0.05$), (Fig. 3a-b).

The LN concentrations of mature leaves in this study (15.32-27.05 milligram per gram (mg/g) (Fig. 3a) were close to the range of values of other mangroves elsewhere (18.52-22.03 mg/g from Jiulong River, southeastern China (Wei *et al.,* 2023); 9.4-10.6 mg/g from Central Red Sea (Almahasheer *et al.,* 2018); 8.4-9.6 mg/g from Palawan, Philippines (Padilla *et al.,* 2004). LP concentrations from these stands (1.30-1.92 mg/g) were 78-96% higher than in natural mangrove forests in the world (0.7 mg/g from Bocas del Toro, Panama (Lovelock *et al.,* 2004); 0.66-0.73 mg/g from Palawan, Philippines, (Padilla *et al.,* 2004), possibly due to an efficient P nutrient resorption strategy. Phosphorus limitation in *R. mangle* has been reported in mature leaves with P concentrations < 0.04 mg/g (Feller *et al.,* 2002). Conversely, the mature leaves examined in various stand types within this study exhibited P

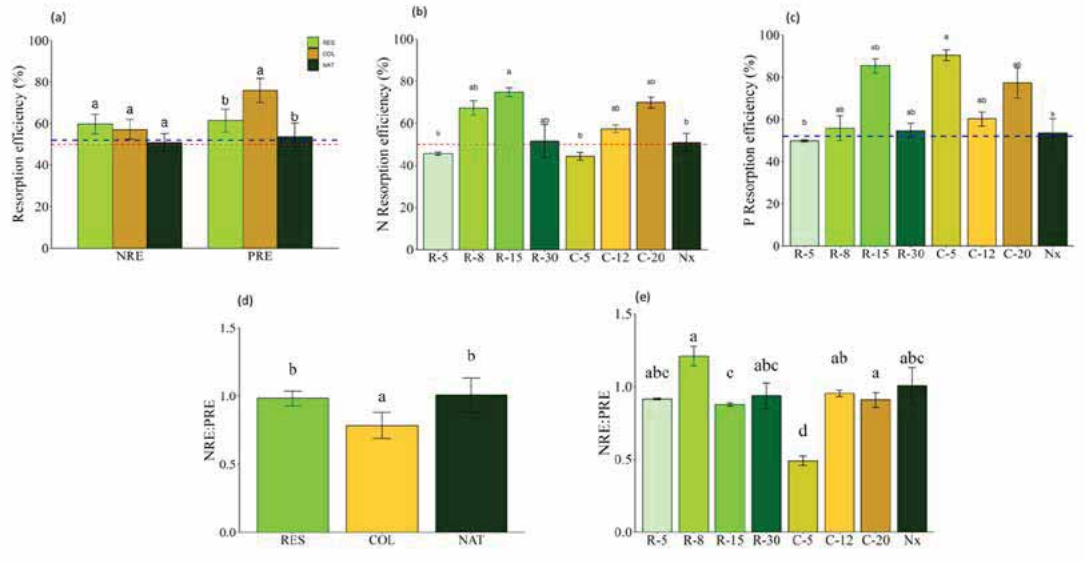


Fig. 4: Nitrogen and phosphorus resorption efficiencies according to (a) stand type, (b-c) stand age, and NRE:PRE ratio according to (d) stand type, (e) and stand ages

Different letters above the error bars indicate a significant difference between stand types or stand ages (at α = 0.05; Tukey's HSD test). Red and blue dashed lines indicate global mean NRE (50%) and PRE (52%).

concentrations that varied between 1.30 and 1.92 mg/g. Although vegetation recovery is apparent in COL stands, senescent leaves contain relatively lower P (Fig. 3b) because of higher resorption (as evidenced by high PRE, 75.99%), presumably to meet plant P demand for survival. The mean N:P ratio (10.8-13.2; Fig. 3c-d) is 20-34% lower than the global mean ratio (16.5), (Tian *et al.,* 2018). The differences observed may stem from the diverse mechanisms of nutrient utilization and cycling that occur among various stand types. The NRE in RES (60%) and COL (57%) stands were higher than the global mean NRE ~50% (Aerts and Chapin, 1999), (Fig. 4a-b), and N in senescent leaves across stand types (7.4-8.7 mg/g) and stand ages (Fig. 3a-b). These values were close to 7 mg/g (Fig. 4a), indicating relative complete resorption of N (Killingbeck, 1996). This indicates that the RES and COL stands may be less efficient in nitrogen conservation, or that the species within these stands do not predominantly depend on N resorption to meet N demand. The PRE in COL stands (76%) were markedly higher than the global mean ~52%, $p < 0.01$ (Aerts and Chapin, 1999), (Fig. 4a-c). P in senescent leaves from COL stands (0.4±0.07 mg/g) was < 0.5 mg/g indicating complete resorption (Killingbeck, 1996). These results imply that species in COL stands are extremely conservative of P. This is a novel evidence for P resorption in disturbed mangroves as observed in the recolonized stands. Complete resorption is common in nutrient-limited environments (Shi *et al.,* 2024) consistent from the *Picea* and *Betula* plantations in Datong County, China where roots mainly absorbed N from soil and P from litter (Liu and Wang, 2021). The fertilization experiment serves as a straightforward approach to assess nutrient limitation (Lovelock *et al*. 2004). Nevertheless, this approach may incur significant expenses, and the meta-analysis did not reveal any clear large-scale trends regarding nutrient limitation (Du *et al.,* 2020). Alternatively, thresholds of leaf N:P ratio (for example, 14:1 versus 16:1 or 10:1 versus 20:1) are widely used to indirectly infer N or P limitation based on the leaf nutrient concentrations (Güsewell, 2004). While these ratios are extensively utilized in terrestrial ecosystems, they were primarily derived from temperate plant species (Sun *et al.,* 2023). In this study, the N:P ratio in mature leaves from all stands was < 14, suggesting a more pronounced N limitation in COL stands (10.8). This situation can be attributed to the long-term consequences of soil excavation that occurred during the construction and subsequent operation of the pond, resulting in a

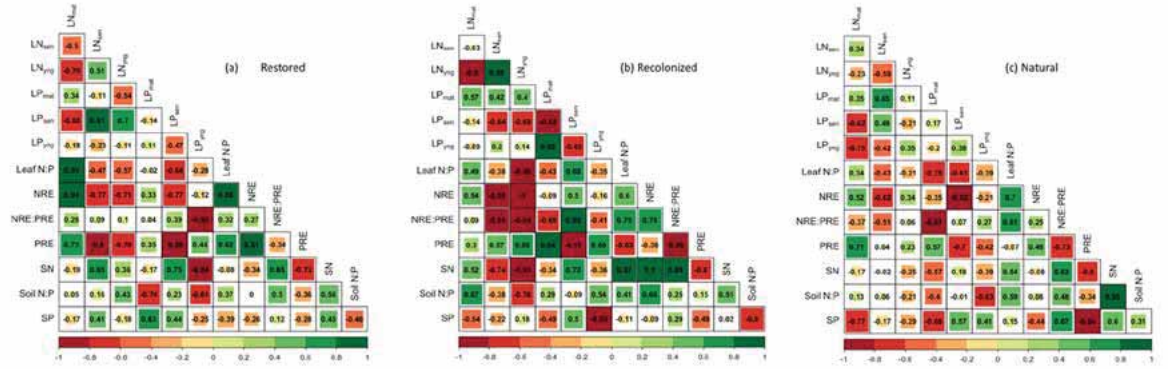


Fig. 5: Heat maps of correlation coefficients between soil and leaf nutrients, leaf nutrient ratios, and nitrogen and phosphorus resorption efficiencies in (a) restored, (b) recolonized, and (c) natural mangrove stands

Note: Significant positive correlations are visualized in blue while significant negative correlations are in red. Color intensities and the sizes of the squares are proportional to the correlation coefficients. LN_{mat} or LP_{mat}, LN_{sen} or LP_{sen}, LN_{yng} or LP_{yng}, NRE, PRE, NRE: PRE, Soil N:P, SN and SP.

diminished N content in the soil. (Adame *et al.*, 2018). Recently, resorption efficiency ratio (NRE:PRE > 1 and NRE:PRE < 1 indicate N and P limitation, respectively) was explored to infer nutrient limitation in mangroves (Shi *et al.*, 2024). However, its dataset focused on terrestrial forest species (Du *et al.*, 2020) and may not be directly applicable to mangrove ecosystems, which are characterized by considerable variability in nutrient availability (Alongi, 2020). NRE:PRE ratio was < 1 in both RES (0.98) and COL stands (0.78), suggesting a more pronounced P limitation in COL stands (Fig. 4d-e). Collectively, the use of leaf N:P ratio and NRE:PRE ratio present conflicting N or P nutrient limitation of mangroves in COL stands. Similarly, Wei *et al.* (2023) observed unclear N or P limitation in *Kandelia obovata* stands in China based on leaf resorption efficiency alone. The effectiveness of either the leaf N:P ratio or nutrient resorption efficiency (RE) as indicators of the nutrient status in mangrove species is still uncertain. These findings highlight that leaf N:P ratio (Güsewell, 2004) and NRE:PRE ratio (Du *et al.*, 2020) have the potential to introduce uncertainty in detecting nutrient limitations in mangroves. This may be due to the 1) highly variable environmental conditions in the mangrove ecosystem, and compounded by the 2) long-term/persistent effect of mangrove conversion to aquaculture ponds. In the Philippines, mangroves exist in a variety of stand conditions (natural, recolonized, and restored) based on vegetation structure and the developmental stage (Corcino *et al.*, 2023). These mangroves are also frequently affected by natural and anthropogenic disturbances such as typhoons and conversion to aquaculture ponds (Salmo, 2021). The unique conditions associated with mangrove ecosystems are generally less evident in the majority of terrestrial forests, which may result in their exclusion from the development of the conventional nutrient ratios. Caution should be taken in using these ratios to predict plant nutrient status in mangroves. It is recommended to establish specific indices for the leaf nitrogen to phosphorus (N:P) ratio and the nitrogen resorption efficiency to phosphorus resorption efficiency (NRE:PRE) ratio in mangrove ecosystems to achieve a more accurate assessment of their nutrient status.

Weak correlation between soil nutrient availability and resorption efficiency

Soil nutrient concentrations (SN and SP) were not significantly correlated with leaf nutrient concentrations in all leaf stages (LN or LP; $p > 0.05$) and stand types, nor with resorption efficiency (NRE or PRE). In NAT stands, SP was significantly correlated with PRE ($r^2 = -0.94$, $p = 0.005$) while SN was significantly correlated with NRE ($r^2 = 0.90$, $p = 0.014$), (Fig 5a-c).

A strong relationship between the nutrient levels in soil and those in leaves was anticipated, given that plants primarily derive their nutrients from the soil (Wei *et al.*, 2023). The results of this study however showed varying weak to moderate correlations between soil nutrient (SN or SP) and leaf nutrient concentrations in all leaf stages across stand types (r^2 = -0.17-0.63, $p > 0.05$), (Fig. 5a-c). This indicates that the concentrations of nutrients in the leaves of mangroves

in Ormoc Bay are not predominantly influenced by soil nutrient levels, suggesting the existence of alternative contributing factors. This contrasts with propositions of direct relationship of mangrove nutrient status with soil nutrients in natural mangroves as observed in the Sundarbans of Bangladesh (Rabiul *et al.,* 2019) and Jiulong River in southeastern China (Wei *et al.,* 2023). The majority of NRE and PRE across stands were not significantly correlated with NA (SN and SP; r^2 = -0.08-0.49, p > 0.05). This observation aligns with findings related to other evergreen species, as the majority of these plants did not exhibit a stable correlation between nutrient RE efficiency and NA availability (Yuan and Chen, 2015). Previous reports on mangroves showed that increasing N availability in soils does not strictly imply an increase in net primary productivity (NPP) and assimilation of extra N (Reis *et al.,* 2017) but instead the need to develop nutrient conservation schemes. Senescent leaves constitute the majority of litterfall in mangrove ecosystems (Pradisty *et al.,* 2022). Leaf litter is a repository of nutrients (Liu and Wang, 2021), and its nutrient ratio affects the quality and rate of nutrient return in ecosystems (Mamidala *et al.,* 2023). In the present study, the N and P concentrations decreased with leaf senescence across stand types (Fig. 3a-b) and stand ages (Fig. 3d), indicating that nutrients were translocated to other parts of the plant before leaf senescence. This expectation arises from the recognition that nutrient resorption serves as a crucial strategy for nutrient conservation, allowing for the recycling of nutrients and minimizing reliance on external sources (Sun *et al.,* 2023). The NRE and PRE of RES and COL stands were significantly higher than NAT stands although COL stands have higher PRE than NAT stands (Fig. 4a-b). Because of the high P resorption in COL and RES stands, it is assumed that the nutrient of senescent leaves, once shedded, contain lower P relative to N. Therefore, leaf shedding would result in the long-term accumulation of N into the detritus matrix as a substantial N pool. Conversely, the process of P resorption during leaf senescence appears to be the primary mechanism for nutrient conservation that addresses the P requirements of mangroves in RES and COL stands. The analysis revealed that there were no significant trends in soil nutrients, leaf tissue nutrient concentrations, or nutrient resorption efficiency in relation to the age of the stand. In RES stands, stand structure differences (i.e. dense monospecific planting in R8, (Table 1) and varying tidal position may strongly influence nutrient variations. A study conducted in the Quanzhou Bay Mangrove Reserve revealed that as the age of restored mangrove stands increases, there is a notable enhancement in soil multifunctionality. This improvement is attributed to the development of microbial communities that are closely linked to N and P cycles (Hu *et al.,* 2024). In contrast, soil inorganic P in a chronosequence of restored mangroves in Guanabara Bay, Brazil does not necessarily increase with mangrove age (Silva *et al.,* 2024). The dense vegetation in R8 and C5 (Table 1) may indicate vegetation recovery, however P resorption is extremely high in COL stands probably as a result of P depletion due to soil excavation and vegetation clearing during pond construction. As a result, leaf litter in COL stands contribute poorly to soil P pool. In COL stands, long-term effects of pond construction (e.g., removal of vegetation, soil excavation) possibly resulted in the alterations of soil recovery including rates and pathways of soil microbial processes which can affect NA (Loiola *et al.,* 2023). Additionally, variations in extractive pressures and the management practices of ponds could account for the discrepancies observed in the age of stands, as well as the concentrations of nutrients in both soil and leaves, along with the efficiencies of nutrient resorption. Differences in tidal water flow (i.e. remnants of large waterways [C5], and dikes that are partially destructed [C20] vs intact [C12]) will either increase/ decrease tidal inundation frequency (Alongi, 2020) and subsequently nutrient input/ output through tidal flushing (Singh *et al*., 2015). These site-specific differences (rather than stand age) may strongly affect nutrient cycling.

This study highlighted the intricate and dynamic nature of nutrient availability and resorption processes in mangroves that are in the process of recovery. This underscores the need for mangrove-specific leaf N:P ratio and NRE:PRE ratio to better characterize the nutrient status of mangroves. Despite the variability in the rates and trends concerning nutrient availability and resorption, mangrove restoration is positively correlated with improvements in soil multifunctionality, microbial diversity, and abundance of genes associated with N and P cycling (Hu *et al.,* 2024). The beneficial effects linked to the restoration of mangroves can enhance both soil health and the resilience of ecosystems as a whole. Thus, pro-active restoration of mid-to upper-intertidal abandoned aquaculture ponds (Lovelock *et al.,* 2022) is highly suggested to enhance nutrient cycling. Consequently,

this fosters the health and development of mangrove forests, thereby enhancing the overall productivity of the ecosystem. Mangroves are predominantly found in estuarine and bay environments, where significant quantities of N and P-rich sediments are both transported and deposited. Future works can explore how varying levels of N and P affect species diversity (including microbial communities) within mangrove ecosystems, particularly in terms of competition and succession dynamics to understand broader ecosystem implications.

CONCLUSIONS

This study represents the first report on nutrient availability and resorption for Philippine mangroves in chronosequence of restored and natural recolonization stands. The study investigated the changes in soil and leaf N and P, leaf N:P ratio, and NRE:PRE ratio across a chronosequence of RES and COL stands (with NAT stands as reference sites). In contrast to classic successional models, soil nutrients (N and P), leaf tissue nutrient (N and P) concentrations and nutrient conservation (as nutrient resorption from senescence leaf tissue) strategies showed no discernable patterns with stand age. PRE in COL stands, recorded at 76%, exceeds the global average of approximately 52%, indicating that species within COL stands are extremely conservative of P. This is a novel evidence for P resorption in disturbed mangroves as observed in the recolonized stands. It is a well-established knowledge that nutrients accumulate in mangroves through time. However, despite the importance of understanding nutrient dynamics in mangroves, the generality of this accumulation pattern needs further investigation in chronosequences of RES and COL stands. Mangroves habitats are characterized by a scarcity of nutrients, where N and P serve as the main limiting factors for their growth. Conventional approaches to assess nutrient limitation currently rely on terrestrial-based indices of leaf N:P ratio and NRE:PRE ratios. Nevertheless, these indices may not be relevant to mangrove ecosystems that experience significant variations in environmental conditions and disturbances. In Ormoc Bay, Philippines, mangroves of varying stand types exist, including RES, COL, and NAT stands. The approach taken in this study involved the collection of samples from both soil and leaves to perform analyses of their nutrient content. From the nutrient concentrations, leaf N:P, NRE, PRE, and NRE:PRE were calculated. Quantitatively, the results of the study revealed significant variations in soil N and P, leaf N and P in all leaf stages, leaf N:P ratio, and nutrient RE of N and P across stand types and ages. The RES (0.15±0.01%) and COL (0.18±0.01%) stands have 4% and 27% higher SN values than NAT stands (0.14±0.01%). Younger R15 and C5 stands had 43% to 7% lower SN than the NAT stands (0.14±0.01%). LN and LP of mature leaves significantly varied across stand types which increased from young to mature stage, then decreased at senescent stage. Soil nutrient concentrations (SN or SP) were not significantly correlated with leaf nutrients concentrations in all leaf stages and stand types, nor with resorption efficiency. This implies that the presence of nutrients in the soil does not inherently result in their uptake and storage by plants. The efficiency of nitrogen resorption is notably similar among various stand types. The PRE was highest in recolonized stands suggesting that phosphorus resorption is an important strategy to meet phosphorus demand. However, the high PRE in COL stands results to low P concentration of senescent leaves and low P input of senescent leaves to soil P pool. Leaf N:P ratio (<14 indicates N limitation, >16 indicates P limitation) is widely used to indirectly infer N or P limitation based on the leaf nutrient concentrations. NRE:PRE > 1 and NRE:PRE < 1 indicate N and P limitation which was also explored to infer nutrient limitation in terrestrial systems. NRE:PRE ratio was < 1 in both RES (0.98) and COL stands (0.78), suggesting a more pronounced P-limitation in COL stands. Although leaf N:P ratio and NRE:PRE ratio were commonly applied to infer nutrient limitation (mostly in terrestrial systems), such approaches presented conflicting nutrient status of mangroves in this study. This highlights the need for mangrove-specific leaf N:P ratio and NRE:PRE ratio to better characterize the nutrient status of mangroves. The findings revealed that differences in nutrient availability and nutrient resorption during mangrove recovery can occur at varying rates and patterns (to no discernable pattern). This study provides evidence on the complexity and dynamic nature of nutrient availability and resorption in mangroves undergoing recovery. Subsequent studies ought to delve into the recovery of faunal populations, with particular attention to microbial communities, across a more extensive spatiotemporal spectrum, assessing their functional roles in conjunction with nutrient availability and the recovery processes of mangrove ecosystems.

AUTHOR CONTRIBUTIONS

M.E.B. Gerona-Daga has contributed in the conceptualization, methodology, data collection and organization, analysis, writing, and visualization. R.A. MacKenzie was involved in writing the original draft, reviewing, editing, and funding acquisition. L.G. Sumabat-Dacones was involved in writing the original draft, reviewing, and editing. C.F. Naputo contributed to data collection, writing the original draft, reviewing, and editing. S.G. Salmo III, the corresponding author, contributed in the conceptualization, writing, supervision, project administration, and funding acquisition.

ACKNOWLEDGEMENT

This study is supported by the "Assessment and Comparison of Recovery of Biodiversity and Carbon Sequestration in Philippine Mangroves Among Natural, Replanted, and Naturally-recolonized Mangrove Stands" (PEER ManCoRe) Project funded by the National Academy of Sciences (NAS) and the United States Agency for International Development (USAID) under USAID cooperative agreement number [AID-OAA-A-11-00012] through the Partnerships of Enhanced Engagement in Research (PEER) with Grant Number 9-379. M.E.B. Gerona-Daga received a scholarship grant for doctoral fellowship from the Department of Science and Technology-Accelerated Science and Technology Human Resource Development Program (DOST-ASTHRDP). The authors thank LM Severino, R Cala, MF Cabiling, LM Limjuco, and JR Navidad for logistic and technical support.

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

©2024 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	Degrees Celsius
COL	Recolonized stand
cm	Centimeter
C5	5-y naturally recolonized stand
C12	12-y naturally recolonized stand
C20	20-y naturally recolonized stand
ha	Hectares
HCl	Hydrochloric acid
ind/ha	Individuals per hectare
km	Kilometer
Leaf N:P	Leaf nitrogen:phosphorus ratio
LN	Leaf nitrogen
LN_{mat}	Leaf total nitrogen of mature leaves
LN_{sen}	Leaf total nitrogen of senescent leaves
LN_{yng}	Leaf total nitrogen of young leaves
LOI	Loss on ignition
LP	Leaf phosphorus
LP_{mat}	Leaf total phosphorus of mature leaves
LPsen	Leaf total phosphorus of senescent leaves
LP_{yng}	Leaf total phosphorus of young leaves
LW	Landward
MAT	Mature leaves
mm	Millimeter
m^2/ha	Meter square per hectare

mg/g	Milligram per gram
mg/kg	Milligram per kilogram
mV	Millivolts
MW	Midward
N	Nitrogen
N:P	nitrogen:phosphorus ratio
NA	Nutrient availability
NAT	Natural stands
Nx	Natural stands of unknown age
NRE	Nitrogen resorption efficiency
NRE:PRE	Nitrogen resorption efficiency:phosphorus resorption efficiency ratio
P	Phosphorus
PRE	Phosphorus resorption efficiency
pH	Potential of hydrogen
ppt	Parts per thousand
RE	Resorption efficiency
RES	Restored stands
R5	5-y restored 'planted' stand
R8	8-y restored 'planted' stand
R15	15-y restored 'planted' stand
R30	30-y restored 'planted' stand
Soil N:P	Soil nitrogen:phosphorus ratio
SE	Standard error
SEN	Senescent leaves
SN	Soil nitrogen
SP	Soil phosphorus
SW	Seaward
y	Year
YNG	Young leaves

REFERENCES

Adame, M.F.; Zakaria, R.M.; Fry, B.; Chong, V.C.; Then, Y.H.A., Brown, C.J., Lee, SY., (2018). Loss and recovery of carbon and nitrogen after mangrove clearing. Ocean Coast. Manage., 161: 117–126 **(10 pages)**.

Aerts, R.; Chapin, F.S., (1999). The mineral nutrition of wild plants revisited: A re-evaluation of processes and patterns. Adv. Ecol. Res., 30: 1–67 **(67 pages)**.

Almahasheer, H.; Duarte, C.M.; Irigoien, X., (2018). Leaf nutrient resorption and export fluxes of *Avicennia marina* in the Central Red Sea area. Front. Mar. Sci., 5: 309199 **(11 pages)**.

Alongi, D.M., (2020). Nitrogen cycling and mass balance in the world's mangrove forests. Nitrogen, 1(2): 167–189 **(22 pages)**.

Ariyanto, D.; Pringgenies, D., (2024). Carbon sequestration rate in sediment mangroves from natural and rehabilitated mangroves. Global J. Environ. Sci. Manage., 10(4): 1951-1960 **(10 pages)**.

Bakrin Sofawi, A.; Rozainah, M.Z.; Normaniza; O.; Roslan, H., (2017). Mangrove rehabilitation on Carey Island, Malaysia: an evaluation of replanting techniques and sediment properties. Mar. Biol. Res., 13(4): 390–401 **(12 pages)**.

Baloloy, A.B.; Martinez, K.P.; Blanco, A.C.; Neri, M.E.P.; Ticman, K.D.V.; Burgos, D.F.,; Principe, J.A.; Reyes, R.B.; Salmo. S.G.III, Nadaoka, K., (2023). Mapping multi-decadal mangrove forest change in the Philippines: Vegetation extent and impacts of anthropogenic and climate-related factors, in: Leal Filho, W., Kovaleva, M., Alves, F., Abubakar, I.R. (Eds.), Climate change strategies: Handling the challenges of adapting to a changing climate. Climate Change Management. Springer, Cham.

Bandibas, M.; Hilomen, V.V., (2016). Crab biodiversity under different management schemes of mangrove ecosystems. Global J. Environ. Sci. Manage., 2(1): 19-30 **(12 pages)**.

Bourgeois, C.F.; MacKenzie, R.A.; Sharma, S.; Bhomia, R.K.; Johnson, N.G.; Rovai, A.S.; Worthington, T. A.; Krauss, K.W.; Analuddin, K.; Bukoski, J.J.; Castillo, J.A.; Elwin, A.; Glass, L..; Jennerjahn, T.C.; Mangora, M.M.; Marchand, C.; Osland, M.J.; Ratefinjanahary, I.A.; Salmo, S.G. III; Sasmit, S.D.; Suwa, R.; Tinh, P.H.; Trettin, C.C., (2024). Four decades of data indicate that planted mangroves stored up to 75% of the carbon stocks found in intact mature stands. Sci. Adv., 10:27 **(12 pages).**

Chen, J.; Yuan, C.; Zhang, Y.; Wu, J.; Chen, G.; Chen, S.; Wu, H.; Zhu, H.; Ye, Y., (2024) Dredging wastewater discharge from shrimp ponds affects mangrove soil physical-chemical properties and enzyme activities. Sci. Total Environ., 926: 171916 **(10 pages)**.

Contessa, V.; Dyson K.; Vivar Mulas P.P.; Kindgard A.; Liu, T.; Saah, D.; Tenneson, K.; Pekkarinen, A., (2023). Uncovering dynamics of global mangrove gains and losses. Remote Sens. (Basel), 15: 3872 **(22 pages).**

Corcino, R.C.B.; Gerona-Daga, M.E.B.; Samoza, S.C.; Fraga, J.K.R.; Salmo, S.G.III, (2023). Status, limitations, and challenges of blue carbon studies in the Philippines: A bibliographic analysis. Reg. Stud. Mar. Sci., 62: 102916 **(18 pages).**

Corporal-Lodangco, I.L. and Leslie, L.M. (2017). Defining Philippine climate zones using surface and high-resolution satellite data', in Procedia Comput. Sci., 114: 324–332 (**9 pages).**

Du, E.; Terrer, C.; Pellegrini, A.F A.; Ahlström, A.; van Lissa, C.J.; Zhao, X.; Xia, N.; Wu, X.; Jackson, R.B., (2020). Global patterns of terrestrial nitrogen and phosphorus limitation. Nat. Geosci., 13: 221-226 **(6 pages)**.

FAO, (2021a). Standard operating procedure for soil available phosphorus Bray I and Bray II method. Rome, Food and Agriculture Organization, Italy.

FAO, (2021b). Standard operating procedure for soil total nitrogen - Dumas dry combustion method. Rome, Food and Agriculture Organization, Italy.

Feller, I.C.; Mckee, K.L.; Whigham, D.F.; O'neill, J.P., (2002). Nitrogen vs. phosphorus limitation across an ecotonal gradient in a mangrove forest. Biogeochemistry. 62: 145–175 **(31 pages)**.

Güsewell, S., (2004). N:P ratios in terrestrial plants: variation and functional significance. New Phytol., 164(2): 243-266 **(24 pages)**.

Hongwiset, S.; Rodtassana, C.; Pongparn, S.; Umnouysin, S.; Komiyama, A., (2021). Spatiotemporal heterogeneity of mangrove root sphere under a tropical monsoon climate in eastern Thailand. Forests. 12:966 **(15 pages)**.

Howard, J. Hoyt, S.; Isensee, K.; Pigeon, E.; Telszewski, M., (eds) (2014). Coastal blue carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes,

and seagrass meadows. Arlington, Virginia, USA: Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature.

Hu, M.; Sardans, J.; Sun, D.; Yan, R.; Wu, H.; Ni, R.; Peñuelas, J., (2024). Microbial diversity and keystone species drive soil nutrient cycling and multifunctionality following mangrove restoration. Environ. Res., 251(2): 118715 **(10 pages)**.

Jimenez, J.A.; Lugo, A.E., (1985). Tree mortality in mangrove forests. Biotropica., 17:177–85 **(9 pages)**.

Kammann, S.; Hortua, D.A.S.; Kominoski, J.S.; Fett, T.; Gillis, L.G., (2022). Understanding how nutrient limitation and plant traits influence carbon in mangrove-seagrass coastal ecosystems. Limnol. Oceanogr., 67(2): S89-S103 **(15 pages)**.

Kao, W-Y.; Chang, K-W., (1998). Stable carbon isotope ratio and nutrient contents of the *Kandelia candel* mangrove populations of different growth forms. Bot. Bull. Acad. Sin., 39: 39-45 **(7 pages)**.

Killingbeck, K.T., (1996). Nutrients in senesced leaves: Keys to the search for potential resorption and resorption proficiency. Ecology. 77(6): 1716–1727 **(12 pages)**.

Kong, W.; Wei, X.; Wu, Y.; Shao, M.; Zhang, Q.; Sadowsky, M.J.; Ishii, S.; Reich, P.B.; Wei, G.; Jiao, S.; Qiu, L.; Liu, L., (2022). Afforestation can lower microbial diversity and functionality in deep soil layers in a semiarid region. Global Chang. Biol., 28: 6086–6101 **(16 pages)**.

Liu, R., Wang, D., (2021). C:N:P stoichiometric characteristics and seasonal dynamics of leaf-root-litter-soil in plantations on the loess plateau. Ecol. Indic., 127: 107772 **(10 pages)**.

Loiola, M.; Silva, A.E.T.; Krull, M.; Barbosa, F.A.; Galvão, E.H.; Patire, V.F., Cruz, I.C.S.; Barros, F.; Hatje, V.; Meirelles, P.M., (2023). Mangrove microbial community recovery and their role in early stages of forest recolonization within shrimp ponds. Sci. Total Environ., 855: 158863 **(12 pages)**.

Lovelock, C.E.; Feller, I.C.; Mckee, K.L.; Engelbrecht, B.M.J., Ball, M.C., (2004). The effect of nutrient enrichment on growth, photosynthesis and hydraulic conductance of dwarf mangroves in Panamá. Funct. Ecol., 18(1): 25-33 **(9 pages)**.

Lovelock, C.E.; Barbier, E.; Duarte, C.M., (2022). Tackling the mangrove restoration challenge. PLoS Biol., 20: e3001836 **(15 pages)**.

Lu, Z.-X.; Wang, P.; Ou, H.-B.; Wei, S.-X.; Wu, L.-C.; Jiang, Y.; Wang, R.-J.; Liu, X.-S.; Wang, Z.-H.; Chen, L.-J.; Liu, Z.-M., (2022). Effects of different vegetation restoration on soil nutrients, enzyme activities, and microbial communities in degraded karst landscapes in southwest China. For. Ecol. Manage., 508: 120002 **(11 pages)**.

Lugo A.E., (1980). Mangrove ecosystems: successional or steady state? Biotropica. 12(Suppl): 65–72. **(8 pages)**.

Luo, J.; Sun, Z.; Lu, L.; Xiong, Z.; Cui, L.; Mao, Z., (2022). Rapid expansion of coastal aquaculture ponds in Southeast Asia: Patterns, drivers and impacts. J. Environ. Manage., 315: 115100 **(10 pages)**.

Mamidala, H.P.; Ganguly, D.; Purvaja, R.; Singh, G.; Das, S.; Rao, M.N.; Ys, A.K.; Arumugam, K.; Ramesh, R., (2023). Interspecific variations in leaf litter decomposition and nutrient release from tropical mangroves. J. Environ. Manage., 328: 116902 **(10 pages)**.

Motsara, M.; Roy, R., (2008). Guide to laboratory establishment for plant nutrient analysis. FAO Fertilizer and Plant Nutrition Bulletin 19. Rome, Italy.

Naidoo, G., (2016). The mangroves of South Africa: An ecophysiological review. S. Afr. J. Bot., 107: 101–113 **(13 pages)**.

Odum, E.P., (1969). The strategy of ecosystem development. Science, 164:262–70 **(8 pages)**.

Padilla, C.; Fortes, M. D.; Duarte, C.M.; Terrados, J.; Kamp-Nielsen, L., (2004). Recruitment, mortality and growth of mangrove (*Rhizophora* sp.) seedlings in Ulugan Bay, Palawan, Philippines. Trees. 18: 589-595 **(7 pages)**.

Pradipta, N.; Alamsjah, N.A.; Masithah, E.D., (2021). Study of nitrogen (N) and phosphorus (P) in the land of mangrove sediments in ecotourism area Wonorejo Surabaya and coastal area of Jenu Tuban. IOP Conference Series: Earth Environ. Sci., 679:012048 **(6 pages).**

Pradisty, N.A.; Sidik, F.; Bimantara, Y.; Susetya, I.E.; Basyuni, M., (2022). Litterfall and associated macrozoobenthic of restored mangrove forests in abandoned aquaculture ponds. Sustainability, 14(13): 8082 **(19 pages).**

Rabiul Alam, Md.; Mahmood, H.; Biswas, T.; Masudur Rahman, Md., (2019). Physiologically adaptive plasticity in nutrient resorption efficiency of *Avicennia officinalis* L. under fluctuating saline environments in the Sundarbans of Bangladesh. Hydrobiologia. 828: 41–56 **(16 pages)**.

Reis, C.R.G., Nardoto, G.B.; Oliveira, R.S., (2017). Global overview on nitrogen dynamics in mangroves and consequences of increasing nitrogen availability for these systems. Plant Soil. 410: 1–19 **(19 pages)**.

Salas-Rabaza, J.A.; Reyes-García, C.; Méndez-Alonzo, R.; Us-Santamaría, R.; Flores-Mena, S.; Andrade, J.L., (2024) Hydroperiod modulates early growth and biomass partitioning in *Rhizophora mangle* L. Aquat. Bot., 191: 103747 **(11 pages)**.

Salmo, S.G.III, (2021). Assessment of typhoon impacts and post-typhoon recovery in Philippine mangroves: Lessons and challenges for adaptive management, in: Friess, D., Sidik, F. (Eds.), Dynamic sedimentary environments of mangrove coasts. Elsevier.

Salmo, S.G.III.; Lovelock, C.; Duke, N.C., (2013). Vegetation and soil characteristics as indicators of restoration trajectories in restored mangroves. Hydrobiologia. 720: 1–18 **(18 pages)**.

Salvaña, M.J.D.; Osa, J.R.F.; Agudo, G.J.L., (2024). Multidecadal mangrove forest change in Macajalar Bay, Northern Mindanao, Philippines (1950-2020) using remote sensing and geographic information systems. Environ. Monit. Assess., 196: 507 **(19 pages)**.

Shi, X.; Zhang, L.; Liu, C.; Zhang, Y.; Wang, M.; Wang, W., (2024). Variable leaf nitrogen-phosphorus ratios and stable resorption strategies of *Kandelia obovata* along the southeastern coast of China. For. Ecol. Manage., 560: 121822 **(9 pages)**.

Sidik, F.; Adame, M.F.; Lovelock, C.E., (2019). Carbon sequestration and fluxes of restored mangroves in abandoned aquaculture ponds. J. Indian Ocean Reg., 15(2): 177-192 (**16 pages).**

Sidik, F.; Kusuma, D.W.; Priyono, B.; Proisy, C.; Lovelock, C.E., (2021). Managing sediment dynamics through reintroduction of tidal flow for mangrove restoration in abandoned aquaculture ponds, in: Friess, D., Sidik, F. (Eds.), Dynamic sedimentary environments of mangrove coasts. Elsevier.

Silva, G.R.D.; Lázaro, M.L.; Queiroz, H.M.; Ferreira, A.D.; Díaz Ramos, R.A.; Machado, W.T.V.; Otero, X.L.; Ferreira, T.O.; Nóbrega, G.N., (2024). How do replanted mangroves affect phosphorus dynamics in their soils? J. Environ. Manage., 366: 121915 **(12 pages)**.

Singh, G.; Chauhan, R.; Ranjan, R.K.; Balakrishna Prasad, M.; Ramanathan, A.L., (2015). Phosphorus dynamics in mangroves of India. Curr. Sci., 108(10): 1874–1881 **(8 pages).**

Sun, X.; Li, D., Xiaotao, L.; Fang, Y.; Ma, Z.; Wang, Z.; Chenjin, C.; Meimei, L.; Hao. C., (2023). Widespread controls of leaf nutrient resorption by nutrient limitation and stoichiometry. Funct. Ecol., 37(6): 1653–1662 **(10 pages)**.

Tian, D.; Yan, Z.; Niklas, K. J.; Han, W.; Kattge, J.; Reich, P. B.; Luo, Y.; Tang, Z.; Hu, H.; Wright, I.J.; Schmid, B.; Fang, J., (2018). Global leaf nitrogen and phosphorus stoichiometry and their scaling exponent. Natl. Sci. Rev. 5(5): 728–739 **(11 pages)**.

Towatana, P.; Voradaj, C.; Panapitukkul, N., (2002). Changes in soil properties of abandoned shrimp ponds in southern Thailand. Environ. Monit. Assess., 74: 45-65 **(21 pages).**

United Nation General Assembly, (2019). United Nations Decade on Ecosystem Restoration (2021–2030).

Wang'ondu, V.W.; Bosire, J.O.; Kairo, J.G.; Kinyamario, J.I.; Mwaura, F.B.; Dahdouh-Guebas, F.; Koedam, N., (2014). Litter fall dynamics of restored mangroves (*Rhizophora mucronata* Lamk. and *Sonneratia alba* Sm.) in Kenya. Restor. Ecol., 22(6): 824–831 **(8 pages)**.

Wei, L.; Bee, M.Y.; Poh, S.-C.; Garg, A.; Lin, F.; Gao, J., (2023). Soil nutrient distribution and plant nutrient status in a mangrove stand adjacent to an aquaculture farm. Environ. Monit. Assess., 195: 231 **(12 pages)**.

Wei, H.; Deng, Y.; Lin, L.; Wang, J.; Huang, J., (2023). Improved soil composition promotes nutrient recovery during vegetation restoration in karst peak-cluster depressions. Catena (Amst.), 222: 106769 **(13 pages)**.

Xiong, Y.; Jiang, Z.; Xin, K.; Liao, B.; Chen, Y.; Li, M.; Guo, H.; Xu, Y.; Zhai, X.; Zhang, C., (2021). Factors influencing mangrove forest recruitment in rehabilitated aquaculture ponds. Ecol. Eng., 168: 106272. **(9 pages)**.

Yuan, Z.Y.; Chen, H.Y.H., (2015). Negative effects of fertilization on plant nutrient resorption. Ecology, 96(2): 373–380 **(8 pages)**.

AUTHOR (S) BIOSKETCHES

Gerona-Daga, M.E.B, Ph.D., Candidate, Institute of Biology, College of Science, University of the Philippines Diliman, Quezon City, Philippines. Assistant Professor, Division of Natural Sciences and Mathematics, University of the Philippines Tacloban College, Tacloban City, Philippines
- Email: *mbgerona@up.edu.ph*
- ORCID: 0000-0002-2573-2385
- Web of Science ResearcherID: DVL-9724-2022
- Scopus Author ID: 58108059300
- Homepage: https://sites.google.com/up.edu.ph/dayonkitahauptac/academic-divisions/division-of-natural-sciences-and-mathematics/dnsm-faculty

- **MacKenzie, R.A.**, Ph.D., Research Ecologist, United States Department of Agriculture, Forest Service, Koror, Palau, USA.
- Email: *richard.mackenzie@usda.gov*
- ORCID: 0000-0003-3779-787X
- Web of Science ResearcherID: HVJ-1730-2023
- Scopus Author ID: 7201869486
- Homepage: https://research.fs.usda.gov/about/people/rmackenzie

Sumabat-Dacones, L.G., Ph.D., Professor, Institute of Biology, College of Science, University of the Philippines Diliman, Quezon City, Philippines.
- Email: *lsdacones@up.edu.ph*
- ORCID: 0000-0002-6720-2059
- Web of Science ResearcherID: HQL-8685-2023
- Scopus Author ID: 58923214400
- Homepage: https://biology.science.upd.edu.ph/faculty-sumabat-dacones-2/

Naputo, C.F.P., M.Sc. Student, Institute of Environmental Science and Meteorology, College of Science, University of the Philippines Diliman, Quezon City 1101, Philippines
- Email: *cpnaputo@up.edu.ph*
- ORCID: 0009-0002-7557-4925
- Web of Science ResearcherID: NA
- Scopus Author ID: 58903181200
- Homepage: https://mangroveecology.com/

Salmo, S.G.III, Ph.D., Professor, Institute of Biology, College of Science, University of the Philippines Diliman, Quezon City, Philippines.
- Email: *sgsalmo@up.edu.ph*
- ORCID: 0000-0001-6807-4397
- Web of Science ResearcherID: JWL-6235-2024
- Scopus Author ID: 36097541900
- Homepage: https://biology.science.upd.edu.ph/faculty-profile-salmo/

HOW TO CITE THIS ARTICLE

Gerona-Daga, M.E.B.; MacKenzie, R.A.; Sumabat-Dacones, L.G.; Naputo, C.F.P.; Salmo III, S.G., (2024). The role of nutrient availability and resorption efficiency and their impact on nutrient conservation in mangroves. Global J. Environ. Sci. Manage., 10(SI): 37-52.

DOI: 10.22034/gjesm.2024.10.SI.03

URL: https://doi.org/10.22034/GJESM.2024.SI.03

Global J. Environ. Sci. Manage. 10(SI): 53-70, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH ARTICLE

Phenol solutions recovery as water pollutants with eugenol cross-linked diallyl phthalate using supported liquid membrane

A.A. Kiswandono*, N. Ningsih, A.V. Sindiani, Rinawati, H.I. Qudus

Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro, Bandar Lampung City, Lampung 35141, Indonesia

ARTICLE INFO

Article History:
Received 24 May 2024
Revised 30 July 2024
Accepted 05 September 2024

Keywords:
Copoly eugenol-diallyl phthalate
Phenol
Supported liquid membrane
Wastewater

ABSTRACT

BACKGROUND AND OBJECTIVES: The swift advancement of the industrial sector raises concerns due to its detrimental impact on the environment, notably in the production of pollutants, such as organic substances like phenol. These compounds are corrosive and toxic to the environment. The study for transport of phenol using copoly eugenol-diallyl phthalate as a carrier based on membrane of polytetrafluoroethylene with supported liquid membrane method was conducted to handle phenol solution. This study seeks to mitigate phenol waste by employing an 8 percent copolymer of eugenol and diallyl phthalate through the supported liquid membrane method. Furthermore, it aims to assess the effectiveness of phenol transport and separation using this membrane technique. The objectives of this study was contributed to the reduction of phenol solution with copoly eugenol diallyl phthalate 8 percent which was utilized from cross linked eugenol using supported liquid membrane method.
METHODS: This study was carried out with several variations, namely source phase power of hydrogen, receiving phase sodium hydroxide concentration, immersion time for supported liquid membrane, carrier concentration and time transport of phenol. This study for membrane evaluation was conducted to use the parameters such as concentration and type of salt, as well as lifetime. Fourier Transform Infrared Spectroscopy was employed to characterize the membrane, assessing its properties before and after the transport process in order to delineate the functional groups associated wit the membrane. Phenol concentration was determined using an ultraviolet-visible spectrophotometer with 4-aminoantipyrine reagent at a maximum wavelength of 455 nanometer.
FINDINGS: The phenol transport test showed that membrane containing copoly eugenol-diallyl phthalate 8 percent was successful in transporting phenol with the conditions such as power of hidrogen of 5.5 in the source phase, 0.25 molar sodium hydroxide concentration for receiving phase, immersion time membrane was 90 minutes, carrier concentration 0.005 molar for 24 hours. The results of the study revealed that portions of the membrane were damaged during the transport process. This conclusion was further validated by the outcomes of the supported liquid membrane technique and the characterization conducted through Fourier transform infrared spectroscopy.
CONCLUSION: The supported liquid membrane containing copoly eugenol diallyl phthalate 8 percent was able to transport phenol even though some membrane components were lost. The presence of 1 molar sodium nitrate salt enhances the durability of the supported liquid membrane, resulting in a lifespan of 15 days, whereas the membrane without the salt addition only lasts for 6 days. This study has significantly enhanced the recovery of phenol solutions, achieving a phenol recovery rate of 87.77 percent, while also successfully prolonging the lifespan of membrane.

DOI: 10.22034/gjesm.2024.10.SI.04

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
53	8	3

*Corresponding Author:
Email: *agung.abadi@fmipa.unila.ac.id*
Phone: +62813 2912 1722
ORCID: 0000-0002-8145-1959

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the “Show Article”.

INTRODUCTION

The industrial sector did not only make a positive contribution to economic development such as social and technological progress for society, but also has a negative impact in the form of liquid waste. Liquid waste still contains a number of pollutant particles which are dangerous for human health, environmental sustainability and ecosystems (Beulah *et al.,* 2020). Phenol is classified as an organic pollutant that is discharged into the environment, leading to the production of offensive and undesirable odors. Phenol waste in water, even it is lowest concentration and toxic to aquatic organisms such as fish and other marine biota (Alsheri *et al.,* 2017). As an industrial pollutant, phenol is recognized for its corrosive and toxic properties. Its stability renders it a persistent environmental contaminant in industrial waste, highlighting the urgent need for effective solutions to address this issue (Rosly *et al.,* 2018). Phenol pollution in wastewater results in high toxicity which is not good for health and can cause systemic poisoning (Messikh *el al.,* 2017). The efficient processing of phenol waste must reduce the harmful effects caused by phenol waste (Sygoun *et al.,* 2019). As a weak acid, phenol possesses an acid dissociation constant (pKa) of 9.98. The introduction of a strong base like sodium hydroxide (NaOH) facilitates the release of hydrogen ions (H^+), leading to the generation of phenolic ions ($C_6H_5O^-$), which are soluble in aqueous environments. Phenolic water systems can produce unpleasant smeels and be dangerous to humans. Phenol waste is found in several industries such as oil refineries is 6-500 milligram per gram (mg/L), coal processing is 9-6800 mg/L, and petrochemical manufacturing is 2.8-1220 mg/L (Othman *et al.,* 2017). In 2001, overall phenol production was 7.78 x 10^6 tons, 39 percent (%) was the production of bisphenol A., phenolic resin was 27 % (Topkara *et al.,* 2019). Membrane technology, especially in the form of liquid membranes, presents an effective method for minimizing phenol waste or facilitating the recovery of phenol. The supported liquid membrane (SLM) is a liquid membrane technique, an efficient combination method of simultaneous liquid and liquid extraction (Amini *et al.,* 2018). SLM functions as a selective transport technique for a range of compounds, particularly in the context of metal ion transport. Its effectiveness is attributed to the incorporation of a carrier, which enhances the selectivity of the process (Panja *et al.,* 2014). The advantages of the liquid membrane is cost savings high selectivity, efficient separation, and SLM for separation of metal ions. The separation and recovery of metals can greatly benefit from the potential of SLM based on parameters such as metal ion concentration, feed potential of hydrogen (pH), carrier concentration, carrier type, stirring speed, pore size, and receiving phase (Amini *et al.,* 2018). Among various conventional methods, SLM separation technology is recognized as one of the most effective approaches for the recovery of toxic metal ions from a range of sources, including aqueous solutions, hydrocarbons, weak acids and bases, gas mixtures, and biological materials. SLM has process advantages such as low research costs, low energy consumption and easy application (Malik *et al.,* 2011). The SLM technique has demonstrated its effective and broader application (Duan *et al.,*2020), capabilities for the extraction of various aqueous solutions (Pont *et al.,*2018), such as metals Ga(III) from chloride solution (Zhou *et al.,* 2019), carbón dioxide (CO_2) separation from air (Li *et al.,* 2016), and separation of phenol from wastewater (Othman *et al.,* 2017). Kazemi *et al.,*(2013) separated methylane blue dye from textile industry liquid waste using the SLM method with an SLM membrane using mono-(2-ethylhexyl) ester of phosphoric acid (M_2EHPA) and bis-(2-etylhexyl) ester of phosphoric acid (D_2EHPA) as a carrier and vegetable oil as a liquid membrane. The study revealed that the most effective transport of methylene blue dye was achieved with a receiving phase concentration of 0.4 molar (M) acetic acid (CH_3COOH) and a source phase pH of 6 (Reyes *et al.,* 2008). The concentration of phenol, tri-n-octyl phosphine oxide (TOPO) was treated phenol in a ratio of 1:1 with the SLM membrane resulting in 74.3% with 24 hours (h) of the initial phenol in source phase NaOH in receiving phase (Zidi *et al.,* 2011). Phenol transport (PhOH) for SLM using bis(2-ethylhexyl) sulfoxide (BESO), the results obtained were that 91% of PhOH was transported efficiently (Yang *et al.,* 2015). In the context of utilizing SLM for the proficient separation of alkali metal cations, the selectivity of the membrane is primarily determined by the ions' mobility and the variations in energy required for dehydration (Qian *et al.,* 2020). Separation of copper from ammonia solution using SLM containing the carrier N902 extractant (Duan *et al.,* 2020). The SLM process for removing acetic acid from aqueous

solutions, utilizing tri-n-octylamine (TOA) as a carrier and sodium hydroxide as the receiving phase (Harruddin *et al.,* 2016). Kazemi *et al.,* (2014), SLM conducted phenol study using SLM 7 hours extraction (feed concentration: 200 mg/L; carrier concentration 40%, feed pH 2, strip phase concentration 1.1 M). The removal of phenols from coal gasification with the SLM method was conducted, and the rate of phenols exceeded 90% after 120 minutes (min.) (Sun *et al.,*2017). A polymer inclusion membrane (PIM) utilizing a combination of cellulose triacetate and cellulose acetate has been shown to achieve a phenol transport efficiency of 95% in the remediation of phenol solution (Benosmane *et al.,* 2018). Saka *et al.,* (2020) conducted synthesis of coply eugenol diallyl phthalate 4% to reduce phenol solution using the PIM method. Ling and Suah (2017), used Polymer Inclusion Method (PIM) method which consists of bis-(2-ethylhexyl) phosphate (B_2EHP) as the carrier, polyvinyl chloride (PVC) as the base polymer, and dioctyl phthalate (DOP) as the plasticizer. The efficiency extraction was more than 98%. Kiswandono *et al.,* (2024), did malachite green (MG) transport using the PIM method which used polyeugenol as a carrier and obtained a transport percentage of 89.09%. Utilizing the liquid membrane approach for the separation of pollutants, bulk liquid membranes (BLM) with nonionic surfactants have demonstrated an extraction rate of 83.4% for phenol removal (Rosly *et al.,* 2018). Emulsion liquid membrane (ELM) containing ionic liquid in tributyl phosphate with a phenol removal percentage of 99.5% (Balasubramanian *et al.,* 2012). Hasanoğlu *et al.,* (2013) was using an emulsion membrane to remove phenol which resulted in 99.4% of phenol could be removed from the water. Within the discipline of membrane science, a critical area of research involves the utilization of membranes to achieve effective ion separation from various solutions, especially in relation to wastewater treatment processes. This research developed cellulose membranes from biomass because cellulose-based membranes are environmentally friendly (Syukri *el al.,* 2024). The separation process using a membrane will be perfect if the mixture move through the membrane faster than other compounds (Benosmane *et al.,* 2018). Othman *et al.,* (2017) carried out phenol recovery from phenol wastewater using a mixture formulated with ionic surfactant liquid emulsion membranes and produced 83% phenol that could be extracted or recovered. Emulsion Ionic Liquid Membrane (EILM) technique was conducted to recovery of Pb(II) metal using nitric acid and Aliquat336 as a carrier and 82.61% of lead ions were extracted by Aliquat 336, according to the results (Mesli *et al.,* 2018). The study employed an ELM technique to eliminate phenol utilizing surfactants, achieving a transportable phenol removal rate of 83.4% (Rosly *et al.,* 2020). Bukhari *et al.,* (2019) carried out optimized phenol recovery from wastewater using an ionic surfactant liquid emulsion membrane and 83% of phenol was successfully extracted. The research used an Emulsion liquid membrane (ELM) to remove phenol with surfactants and obtained results of 83.4% phenol that could be transported (Yildirim *et al.,* 2017). The structural similarity of benzene rings in both polyeugenol and phenol allows for the formation of pi (π) interactions between them. Furthermore, diallyl phthalate (DAF) can function as an effective cross-linking agent for the diene. Crosslinking causes the molecular weight of the resulting polymer to increase because it produces the DAF eugenol copoly. If the molecular weight is greater like active sites (benzene rings and –OH groups) (Kiswandono *et al.,* 2019). The copolymerization of eugenol with diallyl phthalate, known as copoly eugenol diallyl phthalate (Co-EDAF), is projected to augment the active sites present in the polymer, thus improving its efficacy as a carrier in the phenol transport mechanism. Consequently, the present study investigated the treatment of phenolic waste employing Co-EDAF at an 8% concentration through the SLM method, while also assessing the effectiveness of phenol separation achieved by this approach. The findings of Khan *et al.* (2023) further substantiate this claim, demonstrating the use of a carrier to assist in the selection and design of biobased ionic liquids aimed at the separation of formaldehyde. Phenol is a dangerous pollutant that can damage the environment and can harm living organisms, so it is necessary to recover phenol from the environment using the SLM liquid membrane method with Co-EDAF 8% carrier. This study investigates several parameters, namely the potential of hydrogen (pH) in the source phase, the concentration within the receiving phase, the time of immersion, the concentration related to carrier transport time, the characterization of the supported SLM, the effect of different salt types in the source

phase, the influence of optimal salt concentration in the source phase, and the longevity of the system. The aim of this study was contributed to the reduction of phenol solution with Co-EDAF 8% was utilized from cross linked eugenol using SLM method. This SLM method is expected to be an effective method in handling phenol solutions.The target compound was phenol and eugenol cross-linked diallyl phthalate as the carrier both have hydroxyl groups (-OH), so the function of eugenol cross-linked diallyl phthalate can facilitate the transport of phenol as the target from the source phase to the receiving phase. The study significantly contributes to mitigating the effects of phenol waste, a prevalent organic pollutant in aquatic environments. The findings indicate an impressive removal rate of 87.77% of phenolic compounds from contaminated solutions, thereby alleviating environmental pollution. The study has been carried out in the Analytical Chemistry and Instrumentation Laboratory, Department of Chemistry, Faculty and Mathematics and Natural Sciences (FMIPA), University of Lampung and at the UPT Integrated Laboratory and Technology Innovation Center (LTSIT) University of Lampung in 2023 to 2024.

MATERIALS AND METHODS

The main materials were eugenol oil obtained from Ghimas Bologna Company and diallyl phthalate supply from Sigma Aldrich. Other materials were polytetrafluoroethylene membrane (PTFE) with 0.45 micrometer (µm) pore size and 47 millimeter (mm) diameter (Hawach Scientific), phenol (C_6H_5OH) of Nice Chemical, chloroform ($CHCl_3$) of Merck, 4-aminoantipyrine ($C_{11}H_{13}N_3O$) of Sigma Aldrich, potassium ferricyanide [$K_4Fe(CN)_6$], ammonium hydroxide (NH_4OH) of Merck, hydrochloric acid (HCl) of Merck, sodium hydroxide (NaOH) of Merck, sodium sulfate (Na_2SO_4) ACS Grade, dipotassium phosphate (K_2HPO_4) of Merck, monopotassium phosphate (KH_2PO_4) of Aus Chem Source, sodium nitrate ($NaNO_3$) of Merck, sodium chloride (NaCl) of Merck, potassium nitrate (KNO_3) of Merck, and potassium chloride (KCl) of Merck.

Source phase pH

After placing PTFE membrane was in transport pipe (middle of the pipe), 50 milliliters (mL) of 0.1 molar (M) NaOH as receiving phase, and 50 mL of 60 part per million (ppm) phenol, was previously pH-adjusted to 3.5, 4.5, 5.5, 6.5, and 7.5, was added as the source phase. After sealing pipe of transport, a magnetic stirrer was used to homogenize the mixture for nine hours at room temperature. Phenol in both phase (source and receiving phase) was determined maximal wavelength using a ultraviolet visible (UV-Vis) spectrophotometer.

Concentration of receiving phase (NaOH)

The transport pipe was closed and the PTFE membrane was positioned in the center. 50 mL phenol 60 ppm (source phase) with optimal pH and 50 mL of 0.01 molar NaOH were added. The receiving phase consisted of 0.05, 0.1, 0.25, and 0.5 M. The transport pipe was sealed using a magnetic stirrer, which facilitated continuous stirring at ambient temperature for a period of nine hours. Upon the conclusion of the transport, both the source phase and the receiving phase were extracted for analysis. Phenol in both phase (source and receiving phase) was determined maximal wavelength using a UV-Vis spectrophotometer.

Immersion time variation

Various immersion times of one min., thirty min., sixty min., and ninety min., the PTFE membrane was immersed in a solution containing Co-EDAF 8% carrier and placed in the center of the phenol transport pipe. For ideal circumstances, 50 mL phenol 60 ppm (source phase) and 50 mL NaOH (receiving phase) were then added. Once both transport pipes were sealed, a magnetic stirrer was utilized to maintain continuous stirring at room temperature for a total of nine hours. Samples were taken from both the receiving and source phases. Phenol in both phase (source and receiving phase) was determined maximal wavelength UV-Vis spectrophotometer.

Carrier concentration

The optimum immersion, receiving phase concentration, and pH source phase were all considered during the transport process. In the center of the transport pipe was a PTFE membrane with carrier concentrations of 0, 0.005, 0.01, 0.015, and 0.020 M. NaOH 50 mL (receiving phase) and 50 mL phenol 60 ppm (source phase) were then added. The source and receiving phases of the transport pipe were sealed and subjected to continuous stirring at room temperature for a period of nine hours, utilizing

a magnetic stirrer. Samples were taken from both the receiving and source phases. Phenol in both phase (source and receiving phase) was determined maximal wavelength using a UV-Vis spectrophotometer.

Transport time

For ideal conditions, the PTFE membrane (center in transport pipe) and 50 mL NaOH (receiving phase) and 60 ppm phenol 50 mL (surce phase) were added. A magnetic stirrer was employed to seal and agitate the transport pipe for intervals of three, nine, fifteen, twenty-four, and thirty-six hours. Samples were taken from both the receiving and source phases. Phenol in both phase (source and receiving phase) was determined maximal wavelength using a UV-Vis spectrophotometer.

Characterization of SLM PTFE membranes

Fourier transform infrared (FTIR) and scanning electron microscope (SEM) were utilized to analyze the SLM PTFE membrane during the phenol transport optimization technique.

Effect of salt types

After being prepared, the SLM PTFE membrane was weighed before being utilized and put in the center of the transport pipe. During the source and receiving phases, a spin bar was utilized to close and homogenize the transport pipe. The source phase contains variations of the salts NaCl, $NaNO_3$, Na_2SO_4, and KNO_3 at concentrations of 0.01 molar. Samples are collected during the source phase and the receiving phase following the completion of the transportation process. After transport, phenol in both phase (source and receiving phase) was determined maximal wavelength using a UV-Vis spectrophotometer.

Salt $NaNO_3$ concentration

The prepared SLM PTFE membrane is weighed before being used and put in the center of the transport pipe. In the source phase, the optimal salt type $NaNO_3$ was utilized in the closed, homogenized transport pipe. A spin bar magnet was used to transport the salt in changes in concentrations of 0 (control); 0.001; 0.01; 0.1; and 1 M. Following the completion of the transit, samples have been collected at the source and receiving phases. Phenol in both phase (source and receiving phase) was determined maximal wavelength using a UV-Vis spectrophotometer.

Lifetime

Before being transported, the SLM PTFE membrane was weighed and positioned in the center of the transport pipe. The movement of phenol was executed in an environment characterized by optimal optimization parameters. A spin bar stirrer was utilized to close and define the transport receiving and source phases. Samples have been collected from both the source and receiving phases. After transport, phenol in both phase (source and receiving phase) was determined maximal wavelength using a UV-Vis spectrophotometer. Solution of source phase was utilized to test lifetime in five different ways: without salt (control), 0.01 M NaCl salt, 0.01 M $NaNO_3$ salt, 0.1 M $NaNO_3$ salt, and 1 M $NaNO_3$ salt. By taking a pH reading at the source phase, lifetime was calculated. The rise in pH levels observed in the source phase indicated a potential breach in the SLM membrane. The phenol transport process stopped when the pH reached ±9.0, in the source phase which was measured (Kiswandono *et al.,* 2020).

RESULTS AND DISCUSSION

Source phase pH

A significant factor influencing the diffusion of protons, in the presence of differing concentrations between the source and receiving phases, is attributed to the properties of the membrane. In a source phase had a greater proton concentration than the receiving phase. The pH variation used was 3.5; 4.5; 5.5; 6.5 and 7.5. The findings derived from the investigation into phenol transport revealed a correlation between the percentage concentration of the source phase and the percentage concentration of the receiving phase, which is depicted in Fig. 1. The most effective phenol transport which was an optimum condition was in a source phase pH of 5.5 with a phenol concentration of 44.46% because the driving force became very strong because had different substantial pH between the source and receiving phases, so that the phenol transport process increased. At low pH levels, the protons associated with the –OH group of phenol remain bound to the molecule, preventing their release prior to traversing the membrane phase. This phenomenon results in an increased rate of phenol transport. Under conditions of acidic

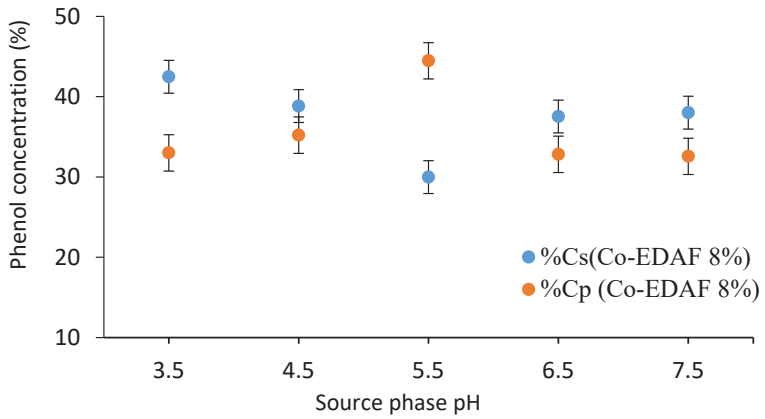


Fig. 1: Percent phenol transported in pH consentration
(Cp : Receiving Phase, Cs : Source phase)

pH, the solubility of phenol in the organic phase is enhanced, resulting in an elevated concentration. In the membrane phase, phenol interacts with carrier molecules through π-π interactions and hydrogen bonds so that phenol will be transported at a higher rate (Fan *et al.,* 2008).

Phenol transport in acidic pH, namely pH 3.5; 4.5; 5.5 caused low efficiency of transport and extraction processes. As the acidity of the source phase rises, a greater proportion of phenol exists in its molecular form, which subsequently hinders the transport of phenol to the receiving phase. Based on Meng *et al.,* (2015), phenol complex after transport was formed through hydrogen bonding. The degree of ionization of phenol became comparatively stronger at higher pH levels (pH>4), which reduced the extent of complexation. The presence of protons in the source phase inhibited the interaction of phenol molecules with the carrier, as the alkaline nature of the receiving phase rendered the transport of phenol ineffective. The highest pH in the source phase of 6.5 and 7.5 of the transported phenol decreased because in these conditions the phenol would be in the form of phenolate so that the hydrogen bonds and π-π interactions between copoly carrier molecule eugenol-diallyl phthalate and phenol on the membrane phase also became weaker. According to Pérez-Silva *et al*. (2018), the investigation into the impact of the feed solution's pH on the transport of phenol indicated a decline in the extraction percentage as pH levels increased, with a notable decrease at pH 11. This observation is largely due to the prevalence of phenolate (charged species) at such high pH.

Concentration of receiving phase (NaOH)

The concentration of NaoH as the receiving phase were carried out at the optimum phenol pH, namely pH 5.5 for 9 hours and in the source phase was phenol 60 ppm. Phenol permeates the membrane phase and is subsequently conveyed to the receiving phase, where it undergoes a reaction with NaOH, resulting in the formation of sodium phenolate. The addition of a stripping agent, NaOH, to the stripping phase serves to obstruct the movement of phenol through the membrane. The stripping agent works to convert phenol into phenolic derivative compounds, specifically sodium phenolates, and traps these compounds in the strip phase, preventing the phenol from returning to the membrane phase (Febriasari *et al.,* 2016). Various concentrations of a strong base (NaOH) were evaluated as stripping solutions to determine the optimal re-extraction conditions for phenol transport (Pérez-Silva *et al.,* 2018). Variations in NaOH concentration used were 0.01; 0.05; 0.1; 0.25 and 0.5 M. The results of phenol transport were in Fig. 2.

Findings from the transport analysis revealed that the ideal concentration was 0.25 M, which resulted in a performance level of 56.30%. The optimum condition at 0.25 M was because this concentration was quite concentrated and had strong basic

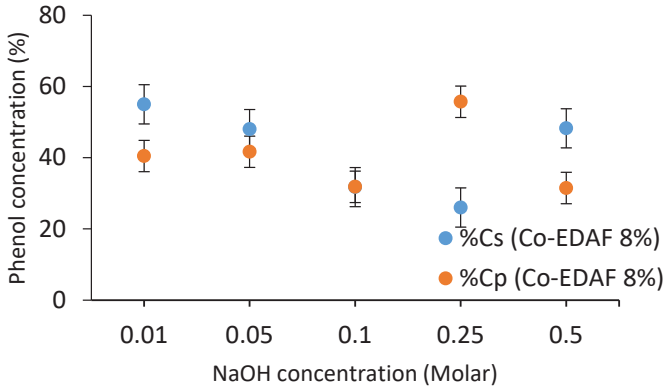


Fig. 2: Percent phenol transported in NaOH concentration (Cp: Receiving phase, Cs: Source phase)

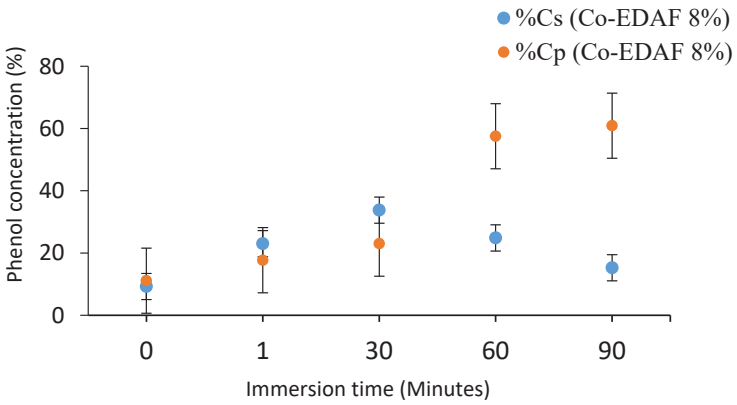


Fig. 3: Effect of immersion time on %phenol transported (Cp: Receiving phase, Cs: Source phase)

properties so that the process of releasing phenolic ions from membrane phase interface the receiving phase was faster with higher concentration of NaOH so that the transported phenol produced increasing phenolic ions. Phenol transport varies in receiving phase 0.01; 0.05; and 0.1 M produced phenol percentages in the receiving phase of 40.48%, 41.68%, and 43.05%. Analysis of the data reveals that an increase in concentration within the receiving phase corresponded to a higher percentage of successful phenol transport. Nevertheless, once the concentration exceeded 0.25 M, a reduction in the transport percentage was observed. The phenol concentration increases at a concentration of 0.01 until 0.25 M due to the high concentration of NaOH, so the release of phenolic ions at the membrane would be faster.

Immersion time variation

Phenol transport studies with varying immersion times on SLM PTFE membranes were carried out at NaOH concentration receiving phase and the pH optimum source phase. The study employed different durations of immersion, specifically 0 hours (indicating no immersion with the carrier), as well as 1 min., 30 min., 60 min., and 90 min. The findings are illustrated in Fig. 3. Based on Syawaliah *et al.* (2018), modifications were carried out by varying the immersion times to 0, 2, 6, and 24 hours. It was proven that the duration of immersion affects the membrane's characteristics and performance. Prolonged immersion of membranes in the phenol solution resulted in the development of thicker layers and enlarged surface membrane pores.

According to Fig. 3, the percentage of phenol

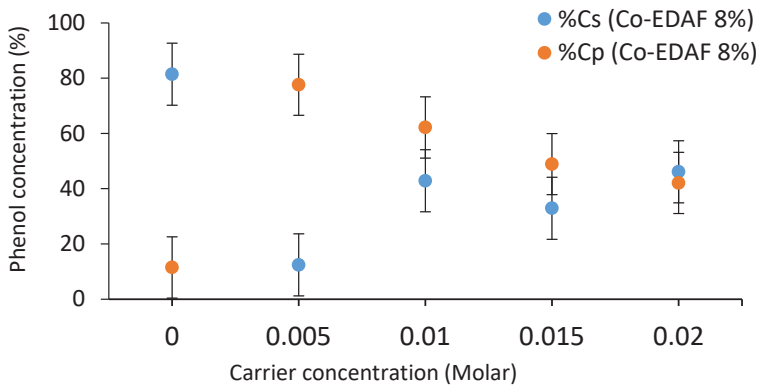


Fig. 4: Effect of carrier concentration on %phenol transported
(Cp: Receivings phase, Cs: Source phase)

concentration effectively transported to the receiving phase increased with increasing membrane immersion time. The most favorable conditions for phenol transport were determined to be a soaking time of 90 min., achieving a rate of 60.94%. Additionally, the length of immersion plays a crucial role in influencing the thickness of the layer. As the immersion time in the solution increases, the membrane surface becomes denser with carriers (Syawaliah *et al.,* 2018). Soaking times < 90 min. resulted in smaller results, namely at 1 min., 30 minutes and 60 minutes of soaking respectively 17.70%, 23.05% and 57.53%. The observed phenomenon can be attributed to the reduced soaking duration, which resulted in the PTFE membrane pores not being entirely saturated with the carrier. In contrast, at a soaking time of 0 minutes, where no carrier was present, the transport of phenol was minimal, recorded at only 11.12%. This showed without any interaction between carrier and phenol, it was difficult for phenol to be transported to receiving phase. The retention of phenol in the membrane phase was influenced by a reduction in the number of carriers present, which complicated the transport process of phenol. This scarcity of carriers led to less than ideal interactions with phenol.

Carrier Concentration

The experiment on phenol transport with varying carrier concentrations was conducted with optimal parameters, including a source phase pH of 5.5, 0.25 M NaOH in the receiving phase, and an immersion time of 90 min. Carrier concentration such as 0 (without carrier); 0.005; 0.01; 0.15 and 0.02 M. A support is essential for the liquid membrane to effectively position the carrier between the feed and receiving solutions. This support must be a hydrophobic, porous material with high chemical resistance to the organic solvents used. The results of phenol transport with varying concentrations of the copoly diallyl phthalate (Co-EDAF) 8% carrier could be seen in Fig. 4. The carrier content in the membrane significantly influences analyte extraction. To improve the conditions for preparation, particularly in relation to carriers like cyanex 923, additional investigation is necessary (Pérez-Silva *et al.,* 2018).

As depicted in Fig. 4, there was a notable rise in carrier concentration, yet the volume of phenol that migrated to the receiving phase was limited. The transport percentage of phenol was 11.48% without a carrier, meaning only a small fraction of phenol was transported because there were no hydrogen bonds or π-π interactions between the carrier and phenol in the membrane phase. The highest phenol transport of 77.63% was obtained with a carrier concentration of 0.005 M. The amount of phenol transported is affected by the carrier concentration present in the membrane phase. Elevating the concentration of carriers in this phase accelerates the formation of phenol complexes, which in turn leads to an increase in the transported phenol (Zidi *et al.,* 2011). An increase in carrier concentration to 0.01; 0.015; and 0.020 M is inversely proportional to the amount of phenol transported to receiving phase. The data indicated that as the concentration of the carrier applied during the immersion process rose, there was a corresponding decline in the amount of phenol that

was successfully transported.

Transport time

The length of the transport time was linked to the amount of time phenol was in the source phase and the carrier was in contact with the membrane. The interaction of phenol with membrane carriers is characterized by the establishment of hydrogen bonds alongside π-π interactions. An extended transport duration correlates with a heightened interaction strength between phenol and the carrier embedded in the membrane. The transport time was varied at 3, 9, 12, 24 and 36 hours using optimum conditions previously obtained using Co-EDAF 8% as a carrier in the SLM membrane. The transport time results was in Fig. 5.

As depicted in Fig. 5, the most effective transport time was determined to be 24 hours, resulting in the transportation of 87.77% of the phenol concentration. The data indicated that the amount of phenol transported to the receiving phase had increased from 0-24 hours. The rationale behind this was the anticipated increase in the volume of phenol being transported. When it was a longer transport time, between phenol (source phase), membrane and NaOH (receiving phase) which was transported into the receiving phase. When transport lasts for 24 hours, the ligand begin to saturate and the amount of phenol transported begin to reach its maximum. The transport time of 36 hours marked a considerable shift in the volume of phenol transported. Extending the transport duration could prove ineffective, given that the quantity of phenol transported was comparatively minimal. With an increase in transport time, the phenol concentration gradient between the source and receiving phases decreased. This reduction in the concentration gradient of the phenol solution leads to a diminished driving force for the movement of phenol from the source to the receiving phase, thereby slowing the transport rate. This was proven by a decreasing percentage of phenol transported during the 36 hours transport time, was 60.87%. The limited number of carriers for optimal interaction with phenol, and there may have been competition for interaction with the carrier, while Phenol was trapped in the membrane and not effectively transported to the receiving phase (Kiswandono *et al.,* 2024).

Characterization of SLM PTFE membranes

The membrane underwent FTIR analysis both before and after the modification to investigate modifications in its chemical structure, particularly the introduction of new functional groups (Tran *et al.,* 2021). FTIR was employed to characterize the SLM PTFE membrane, specifically to ascertain the existence of the hydroxyl (-OH) functional group, which is essential for facilitating the transport process. The results of FTIR characterization could be seen in Fig. 6, explained that the spectra from the analysis of the carrier used was Co-EDAF 8%. The IR spectra obtained before the phenol transport represent the analysis of the PTFE membrane that had previously integrated the carrier. Conversely, the IR spectra obtained after the phenol transport illustrate the analysis of the PTFE membrane that contained the carrier subsequent to its use in phenol transport. Based on Xu *et al.,* (2019), FTIR spectroscopy was used to analyze the surface chemistry of the TODGA-SLM. Each spectrum was recorded in the range of 400

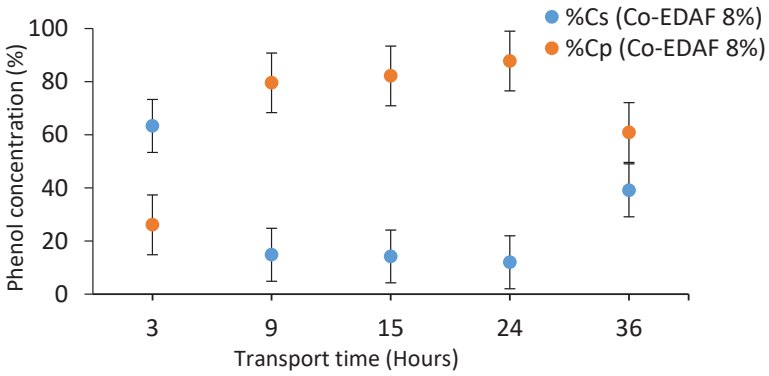


Fig. 5: Percent phenol transported for time
(Cp: Receiving phase, Cs: Source phase)

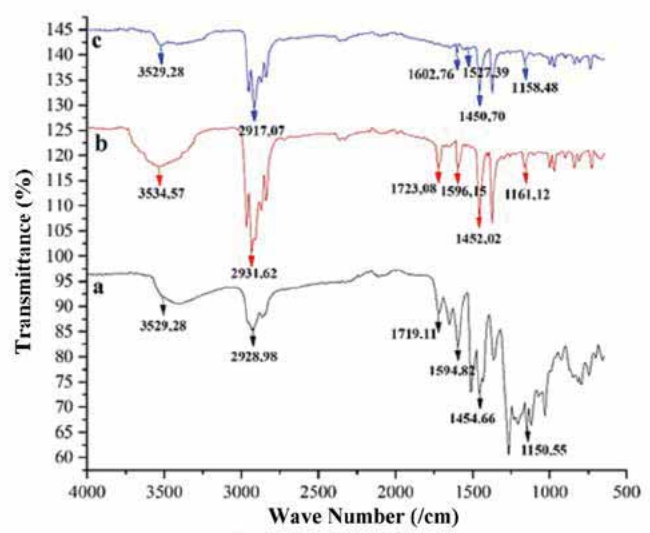


Fig. 6. FTIR characterization results (a) Co-EDAF 8% carrier; (b) Before transport of SLM; (c) After phenol of SLM at 24 hours transport time

Table 1: Functional group comparison resulting from IR PTFE membrane cointained Co-EDAF 8% before and after transport with time transport was 24 hours

Functional group	Wave number per centimeter (/cm)		
	Co-EDAF carrier	Before transport	After tranport
C-H stretching (alkyl)	2928.98	2931.62	2917.07
C-H bending	1454.66	1452.02	1450.70
C=O stretching (carbonyl)	1719.11	1723.08	-
C=C *stretching* (aromatic)	1594.82	1596.15	1527.39
C-O stretching	1150.55	1161.12	1158.48
O-H stretching	3529.28	3534.57	3529.28

to 4000/cm. No significant differences were observed in the FTIR spectra on either side of the TODGA-SLM.

Table 1 provides a representation of the functional groups identified on the membrane.

The broad band in the FTIR spectra with a maximum located near 3500 per centimeter (/cm) can be attributed to hydroxyl stretching in organic compounds (Martínez *et al.,* 2023)**.** A wave number of 3529.28/cm was identified, associated with the stretching absorption of the hydroxyl (-OH) group. This wave number exhibited a pronounced decline in intensity, characteristic of the -OH group, thereby implying a decrease in the quantity of hydroxyl groups present. It indicated that hydrogen bonds have occurred between phenol and the carrier molecule during phenol transport. At the wave number 1594.82/cm, C=C stretching (aromatic) absorption occurs, where phi-phi (π-π) interactions occur, indicating a shift in the wave number after transport. This indicated that there was a benzene ring between π-π interaction in a carrier molecule copoly(eugenol-DAF) and phenol during phenol transport.

Effect of salt types

In source phase, salt was added with a concentration of 0.01 M. The types of salt used in this research were control (without salt), Sodium nitrate ($NaNO_3$), Sodium chloride (NaCl), Sodium sulfate (Na_2SO_4), and Potassium nitrate (KNO_3).Based on Luo and Wan, (2011) as the salt concentration increased, the solute-to-pore size ratio decreased, while the ratio of effective membrane thickness to porosity increased. This implies that the role of salt may encompass a decrease in the size of solutes, an enlargement of the membrane pore size, and an improvement in the effective thickness of the membrane. The effect

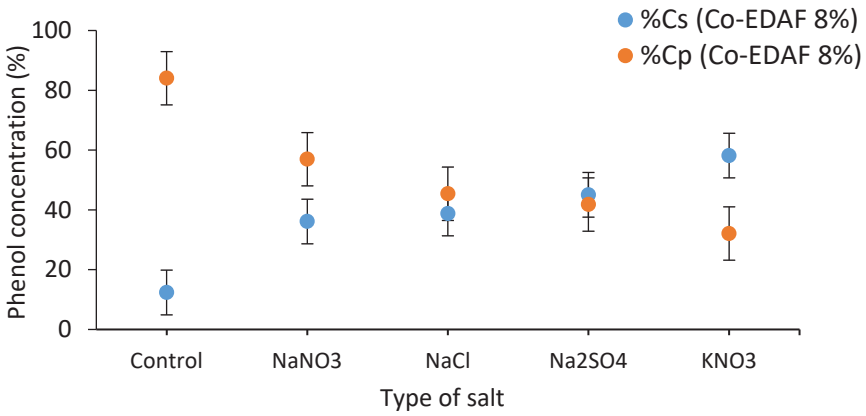


Fig. 7. Effect of salt type
(Cs: Source phase, Cp: Receiving phase)

of introducing various salt types to the source phase on the percentage of phenol transport is depicted in Fig. 7. According to the results (Fig. 7), the type of salt present in the source phase impacted phenol transport for 24 hours, with the phenol at pH 5.5, 90 min., for immersion time, NaOH concentration 0.25 M, and Co-EDAF carrier 8% concentration was 0.01 M. The highest concentration of phenol transported to receiving phase was in control solution which only contained phenol solution without adding salt to the source phase, namely 85.39%.

When the halogenic anion (X) of the salt dissolves in water, hydrogen bonds form between the solvating water molecules and the salt's anion. Vibrational relaxation of the O-H-X system occurs as the O-H group rotates. This rotation breaks the O-H-X hydrogen bond and forms a new O-H-O hydrogen bond with a neighboring water molecule (Kudasheva *et al.,* 2018). The presence of salt in the KNO_3 source phase is associated with a marked decrease in the transport of phenol to the receiving phase, achieving a minimum transport rate of 32.10%. Meanwhile, $NaNO_3$ salt was added in source phase resulted in a good percentage of phenol concentration in receiving phase, namely 56.96%. The lowest number of sodium cation (Na^+) ions will be difficult to bind to the active site (–OH) in the Co-EDAF 8% carrier, so that the interaction of phenol with the carrier was effective in the transport process. Addition of NaCl and Na_2SO_4 salts resulted in phenol transport percentages of 45.42% and 41.80% respectively. The concentration of cations in the phenol solution is directly proportional to the cation content of the salt added. However, when the salt ion concentration in the source phase is elevated, the transport yield decreases, primarily due to the interference caused by the surplus of ions during the phenol transport mechanism. The difference in transport results because NaCl salt was more ionic than $NaNO_3$. Ionic strength greatly influenced the results of phenol transport. The more ionic the salt, it will interfere with phenol transport from source phase to recipient phase. Addition of KNO_3 salt produced lower percentage of phenol compared to the addition of other salts due to the salting-out process. Salting-out was a condition that reduces the solubility of the main substance in a solvent due to salt addition. KNO_3 salt was presence in source phase would interfere with the formation of hydrogen bonds between Co-EDAF 8% and phenol, so that the carrier couldn't facilitate phnenol solution from source phase to receiving phase. Razi and Saien, (2019) investigated the effects of salts with mass fractions of 0.005 and 0.020 in aqueous solutions, demonstrating a marked improvement in the extraction of phenol when compared to systems devoid of salt. The results showed that the presence of salts caused the solute separation factor to reach (46.29% and 95.81%) with NaCl, (63.52% and 165.19%) with Na_2SO_4, and (86.39% and 238.55%) with $MgSO_4$, corresponding to the low and high salt concentrations used. The salting-out effect followed the order $MgSO_4$ more than (>) Na_2SO_4 > NaCl. Alkhudhiri and Hidal, (2017) studied the effects of high concentrations of four salts and three different PTFE membrane pore sizes on

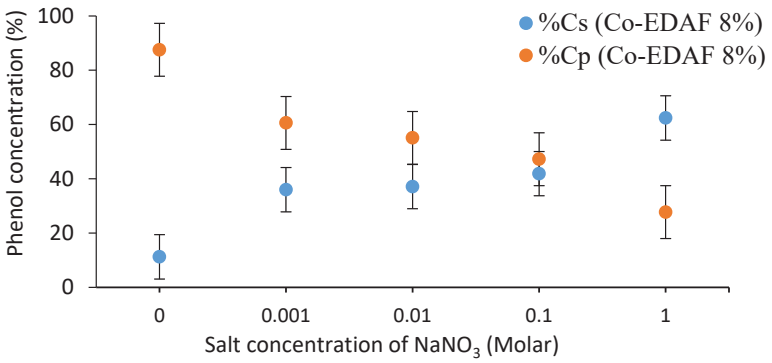


Fig. 8: Effect of salt concentration
(Cp: Receiving phase, Cs: Source phase)

Table 2: pH measurements on SLM membrane lifetime

	pH				
Days	Without salt	NaCl 0.01M	$NaNO_3$ 0.01M	$NaNO_3$ 0.1M	$NaNO_3$ 1M
1	5.14	7.38	7.05	6.26	6.20
3	7.11	7.90	8.59	7.90	6.26
6	9.52	8.08	8.69	8.08	7.95
9	-	9.77	8.86	8.59	8.00
12	-	-	9.07	8.97	8.49
15	-	-	-	9.33	8.54

permeate flux and salt rejection (SR) using an AGMD system. The study showed a significant increase in flux by 39.6% and 56.9% for a maximum NaCl feed concentration of 180,000 mg/L.

Salt $NaNO_3$ concentration

$NaNO_3$ salt concentration was increased by adding $NaNO_3$ salt to source phase, which contained phenol solution 60 ppm then $NaNO_3$ salt concentration was added with 0; 0.001; 0.01; 0.1 and 1 M. The phenol transport process was carried out for 6 hours under pH 5.5 for phenol, NaOH concentration of 0.1 M, 60 min., immersion time and Co-EDAF 8% 0 .01 M. Fig. 8 demonstrates how the addition of varying concentrations of $NaNO_3$ salt and modifications in the source phase influence the percentage of phenol that is transported to the receiving phase.

The introduction of a high concentration of sodium salt into the aqueous phase leads to a reduction in the activity coefficient of water molecules. This alteration subsequently results in an increase in the activity coefficient of the metals, thereby facilitating their transport across the membrane. Membrane pores without the use of salt leak more quickly and the pH in the source phase becomes alkaline more quickly (Zante *et al.,* 2020). The result was showed in Fig. 8 that the highest phenol percentage concentration was efficiently transported to the receiving phase, namely in the control solution or source phase with the addition of 0 M $NaNO_3$ salt, namely 87.55%. Salt concentration was more than 0.1 M, the phenol transported to the receiving phase decreased drastically. $NaNO_3$ was a salt with high solubility, meaning that $NaNO_3$ and phenol can bind water. An increase in the concentration of $NaNO_3$ correlates with a heightened ionic strength of the solution, thereby enhancing the salt's capacity to associate with water molecules. This phenomenon results in a reduction in the solubility of both phenol and NaOH in aqueous environments. This decreased in phenol solubility reduces the ability of the membrane to transport phenol from source to receiving phase. $NaNO_3$ salt addition in the source phase causes Na^+ ions from $NaNO_3$ to bind with -O- to the Co-EDAF carrier in the membrane so that hydrogen bonds occur in phenol and the active side of the carrier will decrease, causing the percentage of phenol transported decreased. According to

Table 3: comparison of phenol transport results with the SLM method

Seperation	Phenol for recovery (%)	Sources
Reducing phenol solutions using the SLM method with a crosslinked agent, namely copoly eugenol divinyl benzene10% (Co-DVB 10%)	91.59	Kiswandono *et al.,* 2024
SLM for the efficient recovery of phenolic compounds, including vanillin and catechol.	76.8	Pavón *et al.,* 2021
Effect and optimization parameters of phenol removal in liquid membrane process	83	Duan *et al.,* 2020
The removal of phenols from coal gasification with the SLM	90	Sun *et al.,*2017
The removal of phenol from aqueous solutions using supported liquid membranes with ionic liquid (IL) as the carrier solvent.	75.63	Duan *et al.,* 2015
SLM phenol study wastewater treatment using Tributyl phosphate and sesame oil	93.14	Kazemi *et al.,* 2014

Kabbani *et al*. (2021), enhancing the ionic strength of the feed solution leads to a diminished effective charge density of the membrane, which permits an increased flow of cations to the permeate side. A charge imbalance is generated, necessitating the movement of anions across the membrane to uphold the solution's electroneutrality, which in turn fosters competition among the anions.

Lifetime

Enhanced stability is indicative of a prolonged operational duration, a characteristic that is highly sought after in practical applications. Most investigators utilize mass flux measurements, and a portion additionally examines selectivity as parameters to gauge the stability of SLM (Saik Su *et al.,* 2022). The lifetime measurement aimed to evaluate the stability of SLM membrane with or without presence of salt. This could be determined by increasing the pH. The stability of the SLM membrane was tested under various conditions and varying salt concentrations, namely without the addition of salt and with the addition of NaCl salt 0.01 M, $NaNO_3$ salt 0.01M, $NaNO_3$ 0.1 M, and $NaNO_3$ 1 M. The findings demonstrate that the type of salt used led to an increased transfer of phenol into the receiving phase, surpassing that of other salts. Table 2 illustrates the correlation between the pH levels of the source phase and the durability of the membrane.

Table 2 showed the lifetime of the SLM membrane that lifetime of the membrane increased to 15 days due to the addition of 1 M $NaNO_3$ salt. The addition of salt had an effect on the %ML Loss because it can decrease the amount of organic phase loss from the membrane thereby increasing membrane lifetime and membrane durability. The transport mechanism involving salt and phenol incorporates water, leading to precipitation and consequently initiating a salting-out phenomenon. Salting-out was a purification method that takes advantage of reduced solubility for certain molecules in solutions that had higher ionic strength. As a consequence, the leakage of the membrane could be mitigated, thereby prolonging its operational life. In the absence of salt, the membrane's longevity is characterized by the absence of sediment accumulation, ensuring that the pores remain unobstructed. Conditions without the addition of salt or the addition of salt at a low concentration, emulsions would easily form, causing the SLM membrane to be unstable. In addition, the increased concentration of $NaNO_3$ added, it was hard to form an emulsion, SLM membrane will be stable. Ragaller *et al.,* (2024), investigated the lifetime sensitivity of the membrane tension probe Flipper in these environments. The application of fluorescence lifetime imaging microscopy (FLIM) to model and biological membranes demonstrated that all probes could identify different membrane phases through their lifetimes. Nonetheless, these probes displayed differing sensitivities to the various biophysical characteristics of the membranes. Finally, this study can recover phenol solution using the SLM method with 8% Co-EDAF carrier, obtaining succesful phenol recovery of 87.77%, as it is referres to the Table 3.

CONCLUSION

The current study concentrated on the reclamation of phenolic solutions, which pose significant risks if

disposed of as waste. The treatment methodology employs a liquid membrane utilizing the SLM technique. Dialyl phthalate as cross linked with a concentration of 8%. Eugenol cross-linked diallyl phthalate as the carrier both have hydroxyl groups (-OH), so the function of eugenol cross-linked diallyl phthalate can facilitate the transport of phenol as the target from the source phase to the receiving phase. The present study investigates multiple variables, such as pH, concentration, time, and the efficacy of the PIM membrane in the transport of phenolic substances. The parameters determined under ideal conditions will be utilized to inform additional testing undertaken in this study. The analysis of test parameters revealed a range of phenol pH values from 3.5 to 7.5, with the optimal pH determined to be 5.5, which produced a result of 44.46%. Furthermore, the concentration of phenol was assessed by varying the NaOH concentration, where the optimal result was recorded at a NaOH concentration of 0.25 M, yielding a concentration of 56.30%. The study examined the immersion time of the SLM PTFE membrane, with various soaking durations tested. The best result was obtained after 90 min., of soaking, leading to transport efficiency of 60.94%, soaking time was longer for the pores of the SLM PTFE membrane to contain carrier Co-EDAF 8% has a lot of -OH active sites so that phenol can be transported to the receiving phase. The concentration Co-EDAF carrier parameter, with optimal conditions found at a 0.05 M concentration, resulting in a transport efficiency of 77.63%. The phenomenon of phenol being released into the receiving phase is linked to the presence of hydrogen bonds or π-π interactions that facilitate this transfer. Variations in transport time were tested, with the optimal transport time of 24 hours achieving an efficiency of 87.77%. This indicateed Co-EDAF 8% effectively driving force phenol towards the receiving phase, aligning with transport time. Upon identifying the optimal conditions, FTIR characterization was carried out on the SLM PTFE membrane to examine the alterations in -OH groups that took place prior to and following the transport. The FTIR analysis showed wave number of 3529.28/cm before transport and a reduction after transport. This change implies that the leaching of -OH groups took place throughout the transport process, with the -OH groups being dissolved as phenol migrated from the source to receiving phase. An evaluation of the membrane durability test was carried out using the parameters of salt type, salt concentration and lifetime of the SLM PTFE membrane. By varying type of salt, $NaNO_3$ was identified as the optimal salt, was 0.01 M concentration with 56.96% phenol transport. The utilization of this specific salt serves to assess the loss of components within the membrane, with the expectation that the incorporation of salt would bolster the stability of the SLM PTFE throughout the duration of transport. The optimum type of salt was $NaNO_3$ salt, this was because this salt had good ionic strength compared to other salts. Subsequently, the ideal form of $NaNO_3$ salt was determined by adjusting its concentration. The optimal concentration identified was 0 M $NaNO_3$ salt, corresponding to 87.55%. This phenomenon can be attributed to the high solubility of $NaNO_3$, which, when combined with phenol, enhances its capacity to bind water. An increase in the concentration of NaNO3 salt resulted in a greater ability to attract water molecules. This happened because ionic of $NaNO_3$ was very high. The final membrane stability parameter was lifetime where this parameter aimed to evaluate the stability of SLM membrane with or without the presence of salt. $NaNO_3$ 1 M salt was added (source phase) for phenol transport made membrane lifetime longer, 15 days compared to without the addition of salt as well as $NaNO_3$ 0.01 M, $NaNO_3$ 0.1 M and NaCl salts with a lifetime of less than 15 days. Stability of the SLM membrane had been tested in various conditions with the lifetime capability of the SLM membrane and can be used repeatedly for 15 days. This study has supported several parameters for successful recovery of phenol solutions using the SLM method supported by Co-EDAF 8% as a carrier. The findings of this study have advanced efforts to mitigate the environmental risks associated with phenol. The methodology adopted is ecologically sound, requiring only a limited quantity of carriers, being economically viable, and characterized by its simplicity in execution.

AUTHOR CONTRIBTIONS

A.A. Kiswandono as the corresponding author was responsible for designing the study, conceptualizing research methods, discussing and executing the research, writing original paper and preparing the manuscript. N. Ningsih was responsible for conducting literature reviews, writing original paper, conducting research experiments, carrying out UV-

Vis analysis also FTIR characterization of samples. A.V. Sindiani was responsible for writing the manuscript, processing research data for UV-Vis data and FTIR data, interpreting the results, and prepared tables and figures. Rinawati was responsible for supervising the experiment and evaluating the data. H.I. Qudus is responsible for manuscript review and manuscript revision.

ACKNOWLEDGEMENT

The study experiment was conducted in Analytical Chemistry and Instrumentation Laboratory and the UPT Integrated Laboratory and Technology Innovation Center (LTSIT) University of Lampung by the team from Membrane Research Department of Chemistry, Faculty of Mathematics and Natural Sciences. The data analysis and preparation of the manuscript was funded by the Ministry of Education, Culture, Research and Technology of Indonesia HETI Project with the [10602/UN26/KS.00.00/2023] commencing on October 16, 2023.

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

©2024 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

>	More than
π-π	Phi-phi
%	Percent
%Cs	Percent of source phase
%Cp	Percent of receiving phase
B_2EHP	Bis-(2-ethylhexyl) phosphate
BESO	Bis(2-ethylhexyl) sulfoxide
BLM	Bulk liquid membrane
CH_3COOH	Acetic acid
C_6H_5OH	Phenol
$C_{11}H_{13}N_3O$	4-aminoantipyrine
$CHCl_3$	Chloroform
/cm	Per centimeter
CO_2	Carbón dioxide
Co-EDAF	Copoly eugenol dialyl phtalate
Co-DVB	Copoly eugenol divnyl benzene
D_2EHPA	Bis-(2-etylhexyl) ester of phosphoric acid
DOP	Dioctyl phthalate
ELM	Emulsion liquid membrane
FTIR	Fourier transform infrared
HCl	Hydrochloric acid
h	Hour
KCl	Potassium chloride
KH_2PO_4	Monopotassium phosphate
K_2HPO_4	Dipotassium phosphate
KNO_3	Potassium nitrate
$K_4Fe(CN)_6$	Potassium ferricyanide
M	Molar
M_2EHPA	Mono-(2-ethylhexyl) ester of phosphoric acid
MG	Malachite green
mg/L	Milligrams per liter
mL	Mililiter

ML Loss	Membran liquid loss
µm	Micrometer
mm	Millimeter
Min.	Minute
Na^+	Sodium cation
NaCl	Sodium chloride
NaOH	Sodium hydroxide
$NaNO_3$	Sodium nitrate
Na_2SO_4	Sodium sulfate
NH_4OH	Ammonium hydroxide
nm	Nanometer
Na_2SO_4	Sodium sulfate
OH	Hydroxyl
pH	Potential of hydrogen
PhOH	Phenol
pKa	Acid dissociation constant
PIM	Polymer inclusión membrane
ppm	Part per million
PVC	Polyvinyl chloride
SEM	Scanning electron microscope
SLM	Supported Liquid Membrane
TOA	Tri-n-octylamine
UV-Vis	Ultraviolet Visible

REFERENCES

Alkhudhiri, A.; Hilal, N., (2017). Air gap membrane distillation: A detailed study of high saline solution. Desalination. 403: 179–186 **(7 pages).**

Alshehri, M.; Saad, Mu.; Naushad, A.; Tansir, A.; Zeid; Aldalbahi, A., (2014). Synthesis, characterization of curcumin based ecofriendly antimicrobial bio-adsorbent for the removal of phenol from aqueous medium. Chem. Eng. J., 254: 181–189 **(9 pages).**

Amini, M.; Rahbar-Kelishami, A.; Alipour, M.; Vahidi, O., (2018). Supported liquid membrane in metal ion separation: An overview. J. Memb., 4(3): 121–135 **(15 pages).**

Balasubramanian, A.; Venkatesan, S., (2012). Removal of phenolic compounds from aqueous solutions by emulsion liquid membrane containing ionic liquid $[BMIM]^+[PF_6]^-$ in tributyl phosphate, Desalination. 289: 27-34 **(8 pages)**.

Benosmane, N.; Boutemeur, B.; Hamdi, S.M.; Hamdi, M., (2018). Removal of phenol from aqueous solution using polymer inclusion membrane based on mixture of CTA and CA. Appl. Water Sci., 8(1) : 17 **(11 pages)**.

Beulah, S.; Muthukumaran, K., (2020). Methodologies of removal of dyes from wastewater: a review. Int. Res. J. Pure Appl. Chem., 21(11): 68-78 **(11 pages)**.

Bukhari.; Muhammad, J.; Norela; Norasikin, O., (2019). Effect and optimization parameters of phenol removal in emulsion liquid membrane process via fractional-factorial design, Chem. Eng. Res. Desalination., 145: 268–278 **(10 pages)**.

Duan, H.; Liu, H.; Hu, C.; Cheng, W.; Wang, X., (2020). Facilitated recovery of copper from ammoniacal solution by supported liquid membrane following multiple cooperative effects. Chem Pap., 74: 3335–3345 **(10 pages)**.

Fan, J.; Fan, Y.; Pei, Y.; Wu, K.; Wang, J.; Fan. M., (2008). Solvent extraction of selected endocrine-disrupting phenols using ionic liquids. Sep. Purif. Technol., 61: 324-331 **(7 pages)**.

Febriasari, A.; Siswanta, D.; Kiswandono, A.A.; Aprilita, N.H., (2016). Evaluation of phenol transport using polymer inclusion membrane (PIM) with polyeugenol as a carrier. J. Rek. Kim. Ling., 11(2): 99–105 **(6 pages).**

Harruddin, N.; Saufia, S.M.; Faizal, C.K.M.; Mohammad, A.W., (2016). Evaluation of different polymeric membrane support for acetic acid removal by supported liquid membrane process. J. Tech. Sci. Eng., 78(12): 13–18 **(6 pages)**.

Hasanoğlu, A., (2013). Removal of phenol from wastewaters using membrane contactors: comparative experimental analysis of emulsion pertraction. Desalination. 309: 171-180 **(9 pages)**.

Huma, W. K.; Amal A.M.; Mansoor. U.l.; Hasan. S.; Berihun, M. N.; Mohd, K. K.; Kashif, K.; Hesam, K.; Mohammad, Y., (2023). Exploring ionic liquids for formaldehyde separation via computational cosmo-rs screening. Chem. Eng. Res. Des. 196: 588-598 **(10 pages).**

Kabbani, H. M.; Al-Hindi, M.; Ayoub, G. M.; Ahmad, M., (2021). The effects of salt concentration on the rejection of pharmaceutically active compounds by nanofiltration membranes. J. Sustainable Dev. Energy Water Environ. Syst., 9(3): 1-16 **(16 pages).**

Kazemi, P.; Mohammad, P.; Alireza, B.; Toraj, M.; Bakhtiari, O., (2013). Pertraction of methylene blue using a mixture of $d_2$ehpa/$m_2$ehpa and sesame oil as a liquid membrane. Chemical., 67 (7): 722–729 **(7 pages)**.

Kazemi, P.; Peydayesh, M.; Bandegi, A.; Mohammadi, T.; Bakhtiari, O., (2014). Stability and extraction study of phenolic wastewater treatment by supported liquid membrane using tributyl phosphate and sesame oil as liquid membrane. Chem. Eng. Res. Desalination., *92*(2): 375-383 **(8 pages)**.

Kiswandono, A.A.; Annur, V.S.; Rizqohayyu, K.K.; Maulana, B. R.; Bagus, K.; Rinawati; Herlian, E.P., (2024). Transport of malachite green using the polyeugenol-based polymer inclusion membrane (pim) method. J. Memb. Sci. Res., 10(1): 1–5 **(5 pages)**.

Kiswandono, A.A., Rinawati, R.; Agustina, W.; Hadi, N.; Nurhasanah, N.; Rahmawati, A.; Nitti, F.; Lusiana, R.A., (2024). Transport of phenol using a supported liquid membrane containing eugenol cross-linked by diallyl phthalate or divinyl benzene as a carrier. J. Memb. Sci. Res.10(3): 1–8 **(8 pages)**.

Kudasheva, A.; Liu, Y. J.; and Ito, A., (2018). Aqueous salt solution liquid membranes, supported by nanoparticles, for water extraction from the atmosphere via air dehumidification. J. Chem. Technol. Biotechnol., 93(10): 2851–2859 **(8 pages).**

Li, J.; Zhao. T.; Sui, G.; Jia, S., (2016). CO_2 Separation from air using microporous polyvinylidene fluoride-supported triethylene glycol/alkanolamine liquid membranes. Mater. Express. 6(2): 183–190 **(7 pages)**.

Ling, Y.; Suah, F., (2017). Extraction of malachite green from wastewater by using polymer inclusion membrane. J. Environ.

Chem. Eng., 5(1): 785-794 **(9 pages)**.
Luo, J., and Wan, Y., (2011). Effect of highly concentrated salt on retention of organic solutes by nanofiltration polymeric membranes. J. Membr. Sci., 372(2): 145–153 **(8 pages).**
Malik, M.A.; Mohd, A.H.; Firdosa, N., (2011). Ionic liquids in supported liquid membrane technology, Chem. Eng. J., 171(1): 242–254 **(12 pages)**.
Martínez, P.A.; Rodríguez, M. E.; de Gyves, J., (2023). MID-FTIR-PLS Chemometric Analysis of Cr(VI) from Aqueous Solutions Using a Polymer Inclusion Membrane-Based Sensor. Memb., 13(8): 1-21 **(21 pages).**
Meng, X.; Gao, C.; Wang, L.; Wang, X.; Tang, W.; and Chen, H., (2015). Transport of phenol through polymer inclusion membrane with N,N-di(1-methylheptyl) acetamide as carriers from aqueous solution. J. Memb. Sci., 493: 615–621 **(6 pages).**
Mesli, M.; Belkhouche, N. E., (2018). Emulsion ionic liquid membrane for recovery process of lead. Comparative study of experimental and response surface design, Chem. Eng. Res. Desalination. 129: 160–169 **(9 pages)**.
Messikh, N.; Bousba, S.; Bougdah, N., (2017). The use of a multilayer perceptron (MLP) for modelling the phenol removal by emulsion liquid membrane. J. Environ. Chem. Eng., 5(4): 3483–3489 **(6 pages)**.
Othman, N.; Noah, N.F.M.; Shu, L.Y.; Ooi, Z.Y.; Jusoh, N.; Idroas, M.; Goto, M., (2017). Easy removing of phenol from wastewater using vegetable oil-based organic solvent in emulsion liquid membrane process. Chin. J. Chem. Eng., 25(1): 45–52 **(8 pages).**
Panja, S.; Ruhela, R.; Das, A.; Tripathi, S. C.; Singh, A. K.; Gandhi, P. M.; Hubli, R.C., (2014). Carrier mediated transport of Pd(ii) from nitric acid medium using dithiodiglycolamide (dtdga) across a supported liquid membrane (SLM). J. Membr. Sci., 449: 67–73 **(8 pages).**
Pavón, S.; Blaesing, L.; Jahn, A.; Aubel, I.; Bertau, M., (2021). Liquid membranes for efficient recovery of phenolic compounds such as vanillin and catechol. Membranes. 11(1): 1–17 **(17 pages).**
Pavón, S.; Fortuny, A.; Coll, M.T.; Bertau, M.; Sastre, A.M., (2020). Permeability dependencies on the carrier concentration and membrane viscosity for Y(III) and Eu(III) transport by using liquid membranes. Sep. Purif. Technol., 239: 1-10 **(10 pages).**
Pérez-Silva, I.; Galán-Vidal, C.A.; Ramírez-Silva, M.T.; Álvarez Romero, G.A.; Páez-Hernández, M.E., (2018). Evaluation of activated composite membranes for the facilitated transport of phenol. E-Polymers, 18(4): 313–319 **(6 pages).**
Pilli, S. R.; Banerjee, T.; Mohanty, K., (2015). Performance of different ionic liquids to remove phenol from aqueous solutions using supported liquid membrane. Desalin. Water Treat., 54(11): 3062–3072 **(10 pages).**
Pont, N.; Salvadó, V.; Fontàs, C., (2018). Applicability of a supported liquid membrane in the enrichment and determination of cadmium from complex aqueous samples. Membranes., 8(2): 21-32 **(11 pages)**.
Qian, Z.; Miedemab, H.; Sahinc, S.; Smet, Sudhölter, E.J.R., (2020). Separation of alkali metal cations by a supported liquid membrane (SLM) operating under electro dialysis (ED) conditions. Desalination., 495: 114631-114647 **(16 pages)**.
Ragaller, F.; Sjule, E.; Urem, Y.B.; Schlegel, J.; El, R.; Urbancic, D.; Urbancic, I;, Blom, H.; Sezgin, E., (2024). Quantifying Fluorescence Lifetime Responsiveness of Environment-Sensitive Probes for Membrane Fluidity Measurements. J. Phys. Chem. B, 128(9): 2154–2167 **(13 pages).**
Razi, A.M.; Saien, J., (2019). Salt effects on liquid-liquid equilibria of water + phenol + (Propan-2-yl) benzene + salts systems. J. Chem. Eng. Data. 64(6): 2414–2422 **(8 pages).**
Reyes, A.J.A.; Gonzalez, M.P.; Navarro, R.; Saucedo, T.I.; Avila-Rodriguez. M., (2008). Supported liquid membranes (SLM) for recovery of bismuth from aqueous solutions. J. Memb. Sci., 310: 13–19 **(6 pages)**.
Rosly, M.B.; Jusoh, N.; Othman, N.; Rahman, H.; Sulaiman, R. N. R.; Noah, N.F.M., (2020). Stability of emulsion liquid membrane using bifunctional diluent and blended nonionic surfactant for phenol removal. Chem. Eng. Process., 148: 107790-107803 **(13 pages)**.
Rosly, N.; Othman; Rahman, H.A., (2018). Liquid membrane component selection for removal of phenol from simulated aqueous waste solution. Malay. J. Anal. Sci., 22(4): 702 – 714 **(12 pages)**.
Saik Su, G.; Morad, N.; Ismail, N.; Rafatullah, M., (2022). Developments in supported liquid membranes for treatment of metal-bearing wastewater. Sep. Purif. Rev., 51(1): 38–56 **(18 pages).**
Saka, C.; Kiswandono, A. A.; Hadi, S., (2020). Synthesis of polymer inclusion membranes based on PVC containing copoly-EDVB 4% as a carrier for removal of phenol solutions, Poll. Res., 39(4): 1009-1016 **(7 pages)**.
Sun, H.; Yao, J.; Li, D.; Li, Q.; Liu, B.; Liu, S.; Cong, H.; Sjak, V.; Feng, C., (2017). Removal Of Phenols From Coal Gasification Wastewater Through Polypropylene Hollow Fiber Supported Liquid Membrane, Chem. Eng. Res. Desalination., 123, 277-283 **(6 pages)**.
Syawaliah, S.; Arahman, N.; Riza, M.; Mulyati, S., (2018). The influences of polydopamine immersion time on characteristics and performance of polyvinylidene fluoride ultrafiltration membrane. MATEC Web of Conference. 197: 1-6 **(6 pages).**
Sygoun, V.; Pantziaros, A.G.; Lakovides; Sfetsa, I.C.; Bogdou, E.; Christoforou, P.I.; Paraskeva, C.A., (2019). Treatment of two-phase olive mill wastewater and recovery of phenolic compounds using membrane technology. Membranes., 9(27): 1-16 **(16 pages)**.
Syukri, H.S.; Kurniawan, F.; Hari, P.D.; Fiana, R.M.; Rini. (2024). Bacterial reduction in river water using nanocellulose membrane from pineapple biomass with ferrous-ferric oxide reinforcement. Global J. Environ. Sci., 10(2): 643–656 **(13 pages)**.
Tran, T.T.V.; Nguyen, C.H.; Lin, W. C.; Juang, R.S., (2021). Improved stability of a supported liquid membrane process via hydrophobic modification of PVDF support by plasma activation and chemical vapor deposition. Sep. Purif. Technol., 277: 1-13 **(13 pages).**
Topkara, D.; Tutkun, O.; Izakov, J.; Shaykieva, N. (2019). Phenol recovery and removal from aqueous solutions by emulsion liquid membranes. MANAS J. Eng., 7(2): 68–73 **(6 pages)**.
Xu, D.; Shah, Z.; Sun, G.; Peng, X.; Cui, Y., (2019). Recovery of rare earths from phosphate ores through supported liquid membrane using N,N,N',N'-tetraoctyl diglycol amide. Miner. Eng., 139: 1-8 **(8 pages).**
Yang, X.; Duan, H.; Shi, D.; Yang, R.; Wang, S.; Guo, H., (2015). Facilitated transport of phenol through supported liquid membrane containing bis(2-ethylhexyl) sulfoxide (BESO) as the carrier, Chem. Eng. Process. Process Intensif., 93: 79–86 **(7**

pages).
Yildirim, M.; Sumnu, G.; Sahin, S., (2017). The effects of emulsifier type, phase ratio, and homogenization methods on stability of the double emulsion, J. Dispersion Sci. Technol., 38(6): 807–814 **(7 pages)**.
Zhou, H.; Zhang, X.; Lv, T.; Guo, Q.; Wang, L., (2019). Comparative study of solvent extraction and supported liquid membrane for the extraction of gallium (III) from chloride solution using organophosphorus acids as extractants, Sep. Sci. Technol., 3012-3027 **(15 pages)**.
Zidi, C.; Tayeb, R.; Dhahbi, M., (2011). Extraction of phenol from aqueous solutions by means of supported liquid membrane (MLS) containing tri-n-octyl phosphine oxide (TOPO), J. Hazard. Mater., 194: 62–68 **(6 pages)**.

AUTHOR (S) BIOSKETCHES

Agung. A.K., Dr., Assistant Professor, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Bandar Lampung City, Lampung 35141, Indonesia.
- Email: *agung.abadi@fmipa.unila.ac.id*
- ORCID: 0000-0002-8145-1959
- Web of Science ResearcherID: NA
- Scopus Author ID: 55532426900
- Homepage: https://kimia.fmipa.unila.ac.id/

Nurhudawati, N., M.Si., Research Assistant, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Bandar Lampung City, Lampung 35141, Indonesia.
- Email: *nurhudawati15@gmail.com*
- ORCID: 0000-0002-3024-5645
- Web of Science ResearcherID: NA
- Scopus Author ID: -
- Homepage: https://kimia.fmipa.unila.ac.id/

Annur, V.S., S.Si., Research Assistant, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Bandar Lampung City, Lampung 35141, Indonesia.
- Email: *sindiannur7@gmail.com*
- ORCID: 0009-0006-1656-9578
- Web of Science ResearcherID: NA
- Scopus Author ID: 58802912900
- Homepage: https://kimia.fmipa.unila.ac.id/

Rinawati, Ph.D., Assistant Professor, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Bandar Lampung City, Lampung 35141, Indonesia.
- Email: *rinawati@fmipa.unila.ac.id*
- ORCID: 0000-0002-8145-1959
- Web of Science ResearcherID: NA
- Scopus Author ID: 55155732500
- Homepage: https://kimia.fmipa.unila.ac.id/

Qudus, H.I., Dr., Professor, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Bandar Lampung City, Lampung 35141, Indonesia.
- Email: *hardoko.insan@fmipa.unila.ac.id*
- ORCID: 0000-0003-3317-6806
- Web of Science ResearcherID: NA
- Scopus Author ID: 57131159900
- Homepage: https://kimia.fmipa.unila.ac.id/

HOW TO CITE THIS ARTICLE

Agung, A.K.; Nurhudawati, N., Annur, V.S.; 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.

DOI: 10.22034/gjesm.2024.10.SI.04

URL: https://www.gjesm.net/article_715544.html

Global J. Environ. Sci. Manage. 10(SI): 71-88, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH PAPER

Impacts of environmental quality and employment resilience during the coronavirus disease 2019 recession and recovery

D.O. Ayuningsih[1], L. Hakim[1,*], A. Suryantoro[1], I. Mafruhah[1], S. Hassan[2], E. Gravitiani[1], N.Q. Fathoni[1], A.I. Hakim[3]

[1] *Faculty of Economic and Business, Universitas Sebelas Maret, Jl. Ir. Sutami, Jebres, Surakarta, Central Java 57126, Indonesia*

[2] *The center of Sustainable Inclusive and Development at the Faculty of Economics and Business, Universiti Kebangsaan Malaysia, 43600, Bangi, Malaysia*

[3] *Department of Anthropology and Sociology, Universitas Kebangsaan Malaysia, 43600, Bangi, Selangor, Malaysia*

ARTICLE INFO

Article History:
Received 28 May 2024
Revised 01 July 2024
Accepted 04 September 2024

Keywords:
Coronavirus disease 2019 (COVID-19)
Demographic
Economic growth
Employment resilience
Environmental quality

ABSTRACT

BACKGROUND AND OBJECTIVES: The unanticipated effects of the economic decline resulting from the coronavirus create both challenges and opportunities for assessing the ability of regions to achieve a balance between their economic demands and the preservation of the environment amidst the upheaval brought about by the pandemic. The objective of this study is to assess the spatial distribution of both the environmental quality index and the employment resilience index within the 34 provinces of Indonesia. This study examines the factors that may influence the environmental quality index during the recession and recovery periods due to coronavirus disease 2019.

METHODS: The present study applies multiple linear regression techniques. The cross-sectional data for this analysis were acquired from the Central Bureau of Statistics, which includes information from 34 provinces in Indonesia during the years 2020 and 2021. This study compares the results of factors that influence the environmental quality index in the 2020 period when the recession was due to coronavirus (resistance dimension) with the 2021 period when the recovery was due to coronavirus (recovery dimension).

FINDINGS: Employment resilience, gross regional domestic product rowth rate, technology and information, population, population density, and the coronavirus recovery rate influence the environmental quality index during the recession and recovery periods due to coronavirus disease 2019, with respective contributions of 75.02 percent and 83.59 percent. In the years 2020 and 2021, the environmental quality index predominantly fell within the good category; however, this distribution was not uniform across the 34 provinces in Indonesia. The categorization of economic resilience and recovery indicates that a majority of provinces in Indonesia are primarily characterized by the group exhibiting positive values in both economic resistance and recovery. Partially, during the recession and recovery periods due to coronavirus disease 2019, technology and information, population, and population density negatively impacted the environmental quality index. During the recovery intervals linked to the coronavirus disease 2019, the recovery index indicated a favorable influence on the environmental quality index.

CONCLUSION: Employment resilience, gross regional domestic product rowth rate, technology and information, population, population density, and the coronavirus recovery rate influence the environmental quality index during the recession and recovery periods due to coronavirus disease 2019. Environmental quality index achievement remains uneven across the 34 provinces in Indonesia. Comparable findings indicate that the economic downturn resulted in diverse responses regarding employment resilience across different geographical areas. Numerous obstacles emerge in the pursuit of sustainable growth. The strategy involves fostering and bolstering support for the green economy, alongside promoting labor development in the renewable energy field, underpinned by heightened investment in green infrastructure.

DOI: 10.22034/gjesm.2024.10.SI.05

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

NUMBER OF REFERENCES
56

NUMBER OF FIGURES
5

NUMBER OF TABLES
8

*Corresponding Author:
Email: *lukmanhakim@staff.uns.ac.id*
Phone: +6281 2268 9145
ORCID: 0009-0004-4523-2056

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

The environmental issue has now become an interesting topic in studying how a region can grow sustainably. The pandemic of coronavirus disease 2019 (Covid-19) has engendered a variety of environmental consequences, encompassing both advantageous and adverse outcomes. The economic decline associated with the pandemic has resulted in unforeseen advancements in the environmental quality (Girdhar *et al.,* 2021). The halt of industrial operations and the decrease in human mobility resulted in a significant decline in pollution levels within Vembanad Lake, recognized as one of the most contaminated freshwater lakes in India (Yunus *et al.,* 2020). Rushayati *et al.* (2020) also noted that the Jabodetabek agglomeration area, one of the Java Ecoregion areas with low air quality, experienced significant air quality improvement during the implementation of emergency public activity restrictions (PPKM). Another positive impact was reported by Praveena and Aris (2021) and (Kamyab *et al.,* 2022), who highlighted improvements in air and water quality due to the Covid-19 pandemic. Contrary to earlier research, the rise in waste generated from personal protective equipment (PPE) has adversely affected the environment throughout the Covid-19 pandemic (Norouzi and Bashashjafariabadi, 2021). The increase in Covid-19 patients has led to a rise in the volume of hazardous waste (Firmansyah *et al.,* 2021). Elevated levels of medical waste and ineffective waste management strategies may contribute to the potential spread of Covid-19 (Abu-Qdais *et al.,* 2020). The lockdown implemented in response to the coronavirus disease-2019 has caused a reduction in activities and the cessation of recycling programs associated with waste management (Zambrano-Monserrate *et al.,* 2020). The environmental quality index (EQI) is a measure of environmental quality in a region of Indonesia. Data shows that the EQI of Indonesia increased by 3.72 points from 66.55 in 2019 to 70.27 in 2020. The increase in the environmental quality index was not evenly distributed across all regions in Indonesia. Based on the 2021 EQI report, some provinces experienced a decline in their EQI value in 2020 (KLHK, 2021). This has driven to explore the factors that may influence the environmental quality index in 34 provinces in Indonesia particularly in light of the challenges posed by the Covid-19. In Indonesia, employment resilience is a critical factor for the stability of the country's economy and social structure. The shock caused by the pandemic has raised the challenge of how quickly Indonesian employment can react and recover from disruptions (recession). Resilience itself is a useful concept for assessing how a region is affected by a recession (Martin *et al.,* 2016). Martin *et al.* (2016) identified three different dimensions of regional economic resilience; a) resistance (indicating the sensitivity of the regional economy to economic shocks); b) recovery (indicating how quickly the regional economy recovers from disruptions); c) reorientation and renewal, which is the ability of a region to adapt in response to shocks and return to its growth path before the recession. Statistical evidence indicates that 1.84 percent, equating to 301.09 thousand employees, experienced job loss in 2020 as a direct consequence of the COVID-19 pandemic (Badan Pusat Statistik, 2021). This data confirms that the Covid-19 shock can pose a significant challenge to the employment sector in Indonesia. The present study investigates the concept of regional resilience, emphasizing the relationship between regional employment and environmental quality. This relationship is explored through two key dimensions: resistance, which assesses the regional economy's susceptibility to economic shocks or downturns, and recovery, which evaluates the rapidity of the regional economy's recovery from such disruptions or recessions, especially in light of the Covid-19. Xaisongkham and Liu (2024) and Bai *et al*. (2021) argued that an increase in the employment has a positive impact on the environment. Other study shows different results, indicating that an increase in employment can reduce environmental quality (Zhong and Su, 2021). Another observation reveals that the escalation of average working hours, driven by an increase in employment, correlates with a rise in carbon dioxide (CO_2) emissions (Fremstad *et al.,* 2019). This is interesting and could be a novel aspect of this research, considering that the role of employment in influencing environmental quality from both recession and recovery perspectives has not yet been a primary focus in studies conducted in Indonesia. Another factor that could affect environmental quality is the gross regional domestic product (GRDP) growth rate. Boosting economic growth often comes at the expense of environmental quality. Rapid economic growth can lead to the over-

exploitation of natural resources, resulting in environmental degradation (Wawrzyniak and Doryń, 2020). This aligns with research showing that increased economic activity gross domestic product (GDP) can lead to higher carbon dioxide emissions (Ekonomou and Halkos, 2023). Other findings also indicate that economic growth impacts the environmental quality index (Amar *et al.,* 2024). The environmental kuznets curve (EKC) theory, developed by Grossman and Kruger, states that there is an inverted U-shaped relationship between per capita income levels (measured by GRDP) and environmental degradation. Once a particular level of income is achieved, there is a corresponding rise in investments directed towards eco-friendly technologies and the enforcement of stricter environmental policies, leading to a decrease in environmental degradation. Rahman *et al.* (2022) and Butarbutar (2023) stated that GRDP has a positive impact on the environment. According to this theory, elevated levels of GRDP may enable and motivate countries or regions to enhance their investments in efforts aimed at environmental preservation (Tang and Wang, 2023). Technology plays a crucial role in linking the economy and the environment. With technological advancement, it is expected to become a key driver in reducing the environmental impact of economic activities. Zhong and Su (2021) and Bai *et al.* (2021) showed that technological changes toward low-carbon technologies slow the growth of carbon dioxide emissions. In contrast, employing technologies that are detrimental to the environment and characterized by high resource consumption can lead to an increase in environmental pollution. This aligns with the research by Awad and Saadaoui Mallek (2023), which suggests that Information and communication technology negatively impacts the environment. Another factor that can influence the environmental quality index is demographic factors. In Indonesia, substantial population growth tends to exert greater strain on natural resources, potentially resulting in environmental degradation if adequate management strategies are not implemented. This aligns with research by Woodard *et al.* (2019), which suggests that population negatively impacts the environment. According to Alnour *et al.* (2022), densely populated urban areas also face greater challenges in maintaining environmental quality. High population density regions often demand significant resources, which consequently contributes to an increase in both waste production and pollution levels. This study incorporates the Covid-19 patient recovery variable, adding novelty to the research. Other studies generally do not directly include this variable when assessing its environmental impact. The recovery of Covid-19 patients presents both challenges and opportunities for environmental quality. Khalid *et al.* (2021) argued that the Covid-19 outbreak prompted a response to consider environmental aspects to support sustainable economic activities. In contrast, the reactivation of various activities and enhanced mobility could reintroduce difficulties regarding environmental quality. It is essential to focus on sustainable economic recovery strategies. Good economic policies must consider their impact on the environment, while environmental policies must also account for economic needs. By considering factors such as employment resilience, gross regional domestic product growth rate, technology, demographic conditions, and the impact of the Covid-19 pandemic, it is hoped that effective strategies can be designed to maintain a balance between human needs and environmental sustainability. This study seeks to investigate the distribution patterns of the environmental quality index and the employment resilience index within the 34 provinces in Indonesia. This study also examines factors that may affect the EQI during the recession and recovery from Covid-19. This study hypothesizes that Covid-19 has had a significant effect on the improvement of environmental quality in multiple regions. The second hypothesis suggests that the expansion of employment sectors is a critical factor influencing the extent of economic resilience and recovery during the Covid-19 pandemic. The third hypothesis is that the employment resistance index (RESIS), recovery index (RECOV), gross regional domestic product growth rate, information and technology, population, population density, and the recovery rate of Covid-19 patients significantly influence the environmental quality index during the recession caused by Covid-19. The fourth hypothesis posits that various factors, including the employment recovery index, the growth rate of gross regional domestic product, advancements in information and technology, population metrics, population density, and the recovery rate of patients affected by Covid-19, have a significant impact on the

Table 1: Description and expected signs of the EQI 2020 variables

Variable and unit	Operational definition	Expected effects on EQI 2020
Variable dependent Environmental quality index Variable independent	The environmental quality Index for the year 2020	
Resis (index)	Resistance is a concept that potentially examines how a region is affected by a recession.	+
Gross regional domestic product growth rate in percent (%)	Growth in the production of goods and services in an economic area within a certain time interval.	-
Information and technologies (%)	Percentage of the population that owns a mobile phone, computer, and accesses the internet	+
Population (person)	Total population, expressed in thousands of people or millions of people.	-
Population density (person)	The number of inhabitants per square kilometer of area.	-
Recovery rate (%)	The recovery rate of coronavirus disease-2019 patients by province.	+

Table 2: Description and expected signs of the EQI 2021 variables

Variable and unit	Operational definition	Expected effects on EQI 2021
Variable dependent Environmental quality index Variable independent	The environmental quality Index for the year 2021.	
Recov (index)	Recovery is a concept that potentially examines how a region recovers from a recession.	+
Gross regional domestic product growth rate (%)	Growth in the production of goods and services in an economic area within a certain time interval.	-
Information and technologies (%)	Percentage of the population that owns a mobile phone, computer, and accesses the internet	+
Population (person)	Total population, expressed in thousands of people or millions of people.	-
Population density (person)	The number of inhabitants per square kilometer of area.	-
Recovery rate (%)	The recovery rate of coronavirus disease-2019 patients by province.	+

environmental quality index throughout the recovery phase from the pandemic. This study was conducted in 34 provinces in Indonesia in 2020 during the Covid-19 recession and 2021 during the Covid-19 recovery.

MATERIALS AND METHODS

Table 1 presents the operational definitions of the dependent and independent variables in Eq. 4 during the Covid-19 recession.

Table 2 presents the operational definitions of the dependent and independent variables in Eq. 5 during the Covid-19 recovery.

Regional employment resistance index

The measurement of the resistance index of the employment data from 2019 and 2020, using Eq. 1 (Cainelli *et al.,* 2019; Ezcurra and Rios, 2019):

$$Resis_i = \frac{\left(\Delta E_i^{\text{Contraction}}\right) - \left(\Delta E_i^{\text{Contraction}}\right)^{\text{Expected}}}{\left|\left(\Delta E_i^{\text{Contraction}}\right)^{\text{Expected}}\right|} \quad (1)$$

Where;

$Resis_i$ is the resistance index of i province; $\Delta E_i^{\text{Contraction}}$ is contraction changes of i province employment; $\Delta E_i^{\text{Contraction}^{\text{Expected}}}$ is contraction change of national employment and $\left(\Delta E_i^{\text{Contraction}}\right)^{\text{Expected}}$ as contraction change of national employment (absolute value).

Regional employment recovery index

The measurement of the recovery index of the employment data from employment data from 2020

and 2021, using Eq. 2 (Cainelli *et al.,* 2019; Ezcurra and Rios, 2019):

$$Recov_i = \frac{\left(\Delta E_i^{Recovery}\right) - \left(\Delta E_i^{Recovery}\right)^{\text{Expected}}}{\left|\left(\Delta E_i^{Recovery}\right)^{\text{Expected}}\right|} \quad (2)$$

Where; $Recov_i$ is the recovery index of i province; $\Delta E_i^{Recovery}$ is recovery changes of i province employment; $\Delta E_i^{Recovery\,\text{Expected}}$ is recovery change of national employment and $\left(\Delta E_i^{Recovery}\right)^{\text{Expected}}$ is recovery change of national employment (absolute value).

Multiple linear regression analysis

This quantitative research is conducted using the multiple linear regression analysis method. Multiple linear regression is a statistical technique used to analyze the relationship between one dependent variable and two or more independent variables (Gujarati and Poter, 2009). The parameters in multiple linear regression are typically estimated using the ordinary least squares (OLS) method, which seeks to minimize the sum of squared errors. For cross-sectional data, the classical assumptions include tests for normality, multicollinearity, and heteroskedasticity. The study utilizes cross-sectional data sourced from the central bureau of statistics, encompassing 34 provinces in Indonesia, with information collected during the years 2020 and 2021. This study aims to compare the factors influencing the environmental quality index during the recession period caused by Covid-19 in 2020 (resistance dimension) with the recovery period in 2021 (recovery dimension) following the Covid-19 recession. This analysis focuses on several independent variables, including the resistance index, recovery index, the growth rate of gross regional domestic product, total population, population density, technology and information factors, as well as the recovery rate of individuals affected by Covid-19, as defined in Eq. 3 (Gujarati and Poter, 2009):

$$Yi = \beta_1 + \beta_2 X_{2i} + \beta_3 X_{3i} + u_i \quad (3)$$

Where; Yi is the dependent variable;; $X2i$, $X3i$ are independent variables; $\beta 1$ is the intercept term; β2,β3 are the coefficients for the independent variables and ui is the error term.

This study uses the multiple linear regression analysis method with the following model, using Eqs. 4 and 5 (Gujarati and Poter, 2009):

$$\text{EQI_2020}_i = \beta_1 + \beta_2 \text{RESIS}_i - \beta_3 \text{LGRDP}_i + \beta_4 \text{IT}_i - \beta_5 \text{POP}_i - \beta_6 \text{PD}_i + \beta_7 \text{RR}_i + u_i \quad (4)$$

$$\text{EQI_2021}_i = \beta_1 + \beta_2 \text{RECOV}_i - \beta_3 \text{LGRDP}_i + \beta_4 \text{IT}_i - \beta_5 \text{POP}_i - \beta_6 \text{PD}_i + \beta_7 \text{RR}_i + u_i \quad (5)$$

Where;

EQI = Enviroment quality index
RESIS = Resistance index
RECOV = Recovery index
LGRDP= Gross regional domestic product growth rate
IT = Information and technologies
POP = Population
PD = Population density
RR = Recovery rate of coronavirus disease-2019 patients

RESULTS AND DISCUSSION

Spatial distribution of environmental quality index

Based on EQI data, the spatial distribution across 34 provinces in Indonesia was categorized and analyzed. The spatial distribution of the EQI for the years 2020 and 2021 generally showed improvement, with most regions falling into the "good" category. Indonesia's EQI increased from 66.55 in 2019 to 70.27 in 2020 and 71.41 in 2021, although this improvement was not uniform across all regions. Lockdowns instituted during the pandemic contributed to a substantial decline in pollution levels in diverse áreas (Masum and Pal, 2020). Other findings also indicate a reduction in emissions during the lockdown period (Gupta *et al.,* 2020) . Rushayati *et al.* (2020) also noted that the Jabodetabek agglomeration area, one of the Java Ecoregion areas with low air quality, experienced significant air quality improvement during the implementation of emergency public activity restrictions (PPKM). The 2020 EQI data showed that 12 provinces were in the "moderate" category, including Bengkulu, South Sumatra, North Sumatra, Lampung, East Java, Central Java, DI Yogyakarta, Banten, West Java, DKI Jakarta, Riau, and South Kalimantan. The 2021 EQI data showed that 10 provinces were in the "moderate" category, including South Sumatra, West Nusa Tenggara, Jambi, Lampung, East Java,

Central Java, DI Yogyakarta, Banten, West Java, and DKI Jakarta. Figs. 1 and 2 highlight that DKI Jakarta had the lowest EQI compared to other provinces. In DKI Jakarta, the substantial population density contributes to a rise in consumption, which presents several environmental risks. Additionally, this dense population fosters greater mobility requirements, prompting the need for transformative innovations, including the implementation of electric vehicles, which can address the challenges associated with sustainable transportation (Farajnezhad *et al.*, 2024). The Covid-19 pandemic led to an increase in the EQI in provinces on Java Island, with the average EQI rising from 52.68 in 2019 to 62.07 in 2020 (KLHK, 2022). In 2021, there was a decline in EQI in Central Java and DI Yogyakarta. To conclude, Java Island recorded the lowest EQI, which is below the average observed at the national level. The significant decline in the EQI value for Java Island can be attributed to the low land quality index (LQI), which is categorized as "poor" and records an average score of 37.46. The low LQI in the Java Ecoregion is due to the disproportionate balance between vegetated land and built-up areas. An expanding population has intensified the demand for land, prompting the alteration of forested landscapes into constructed environments and additional infrastructural projects (KLHK, 2022). In 2021, during the recovery period from Covid-19, the EQI values in the provinces of Bangka Belitung Islands, Jambi, and Aceh showed a decline. This was marked by weak synergy in environmental management in these regions. In these areas, the environmental problems can be attributed to intensified social and economic activities, which have contributed to a deterioration in air quality, a reduction in the quality and quantity of water resources, and an escalation in domestic waste and pollution levels. Bali and West Nusa Tenggara also showed a decline in EQI values. The environmental issues in these regions were largely because Bali and West Nusa Tenggara are tourist destinations. The significant level of human activity in these regions exerts considerable pressure on the environment, as

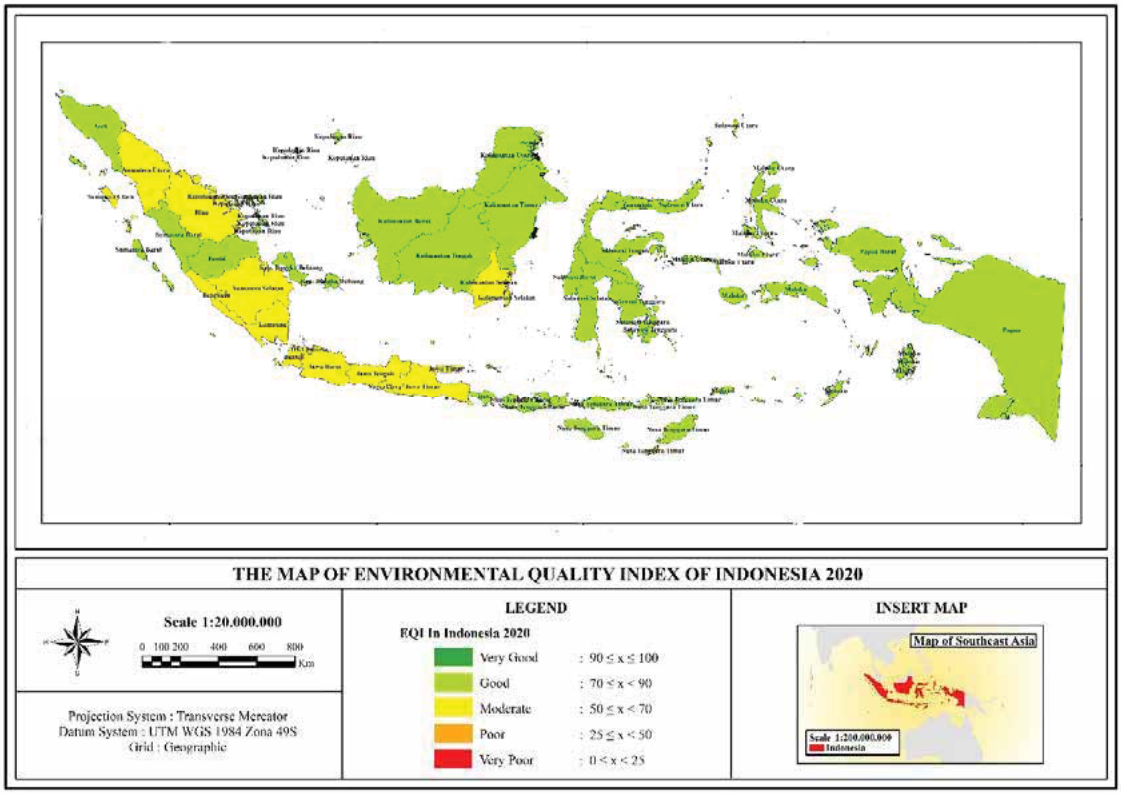


Fig. 1: Spatial distribution of the environmental quality index in 34 Provinces of Indonesia in 2020

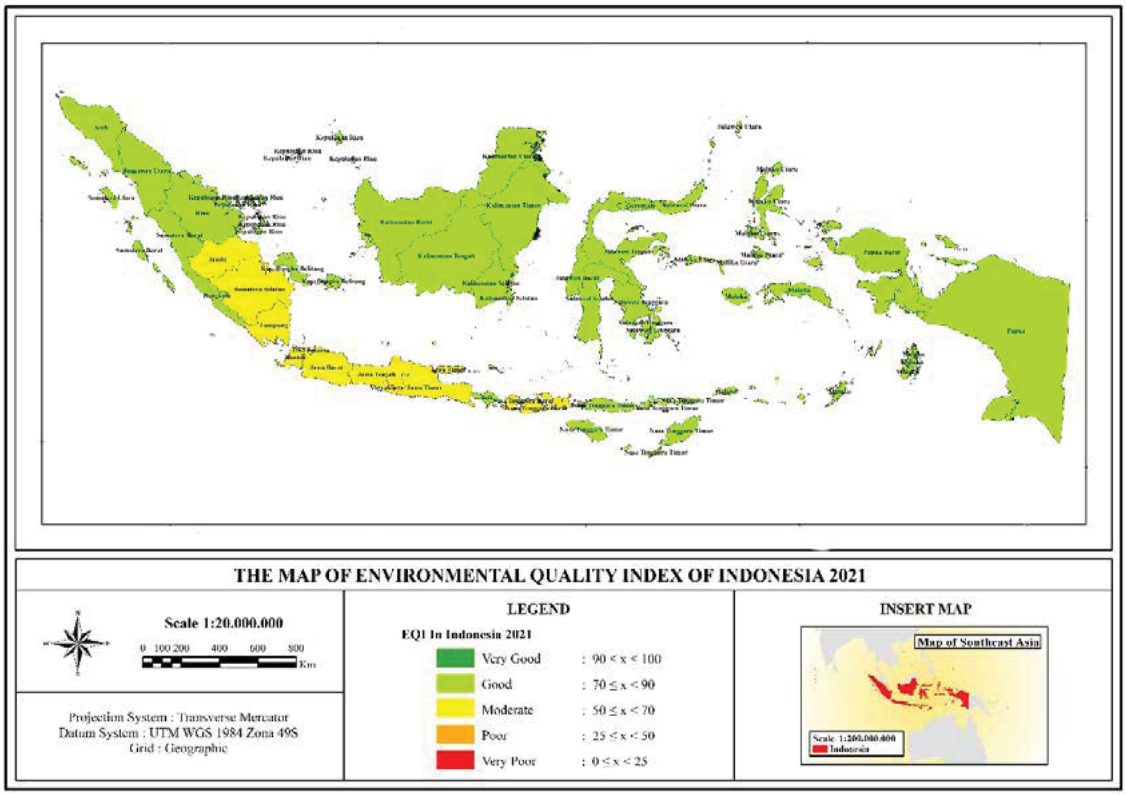


Fig. 2: Spatial distribution of the environmental quality index in 34 Provinces of Indonesia in 2021

evidenced by the rising accumulation of waste in Bali. This situation calls for greater attention from local governments to improve environmental management. In general, the EQI values in Kalimantan, Sumatra, and Papua indicate good environmental quality with scores above the national average. East Kalimantan Province experienced a decline in EQI in 2021, which was caused by pollution resulting from industrial, mining, agricultural, and domestic activities. Central and regional government policies play an essential role in sustaining and reinforcing the synergy of environmental management. Their effectiveness is contingent upon the proper implementation of established regulations and policies, particularly those pertaining to land conservation, pollution control, and waste management. Strengthening regulations as a concrete step to preserve environmental quality can be achieved through reinforcing laws on land conversion, strict supervision of industrial activities, and supporting the development of green infrastructure to help improve environmental quality.

Classification of economic resistance index and economic recovery Index

The coronavirus disease-2019 pandemic that continues to increase in 2020 has an impact on the economy of a region. The measures taken to enforce a lockdown during the Covid-19 pandemic led to substantial economic downturns and extensive interruptions in industrial operations (Caraka *et al.*, 2019). The ability of a region to withstand shocks plays a crucial role in ensuring the stability of its economic framework. Based on the value of resistance and recovery (Figs. 3 and 4), 34 provinces in Indonesia can be divided into four categories. Most areas in Indonesia, including the provinces of South Sumatra, Central Kalimantan, Riau Islands, Southeast Sulawesi, Riau, Banten, West Nusa Tenggara, Maluku, North Maluku, East Nusa Tenggara, and West Papua are included in the positive value economic resistance and recovery group.

Among the provinces, West Papua stands out with the highest resistance level, reflected in its resistance

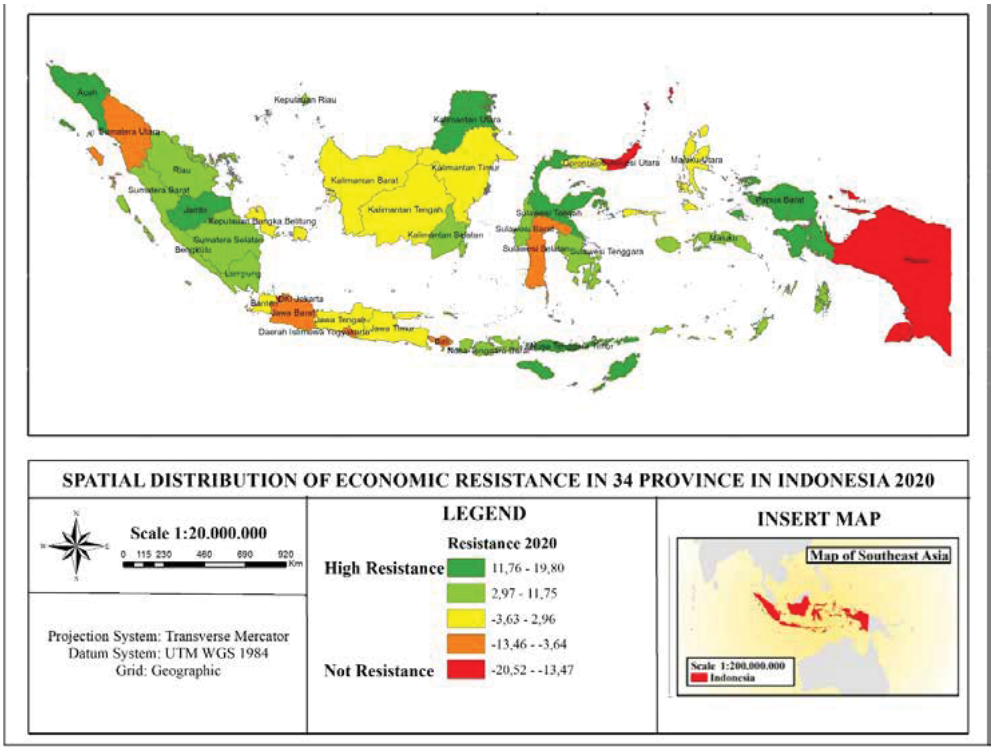


Fig. 3: Spatial distribution of economic resistance in 34 Provinces of Indonesia in 2020

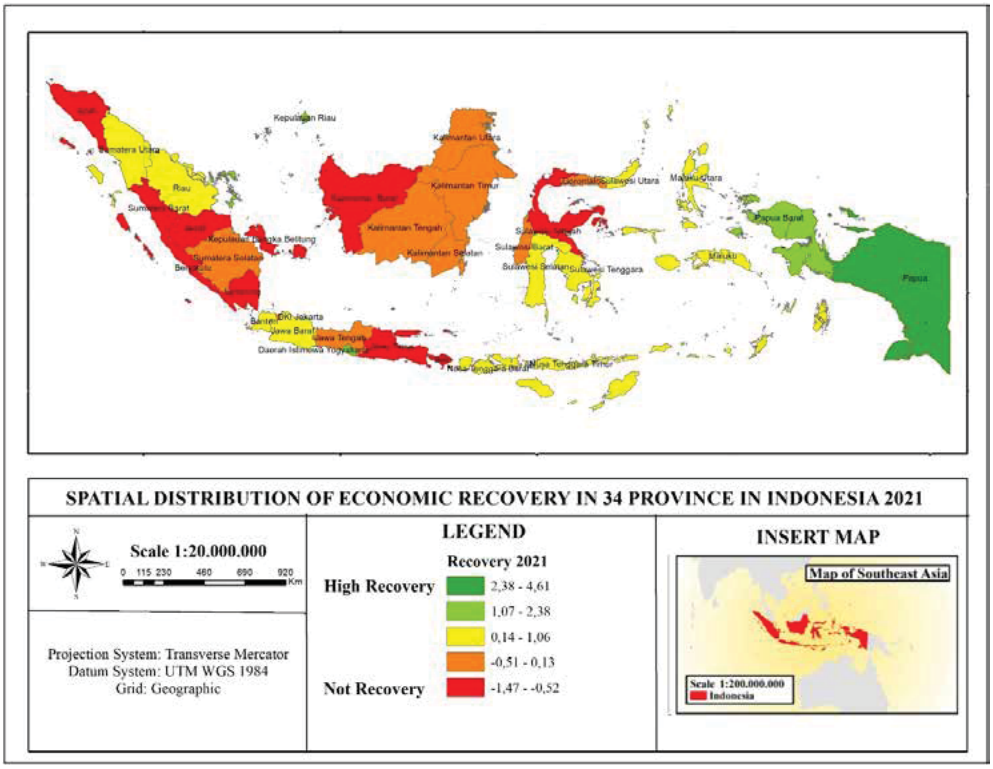


Fig. 4: Spatial distribution of economic resistance in 34 provinces of Indonesia in 2021

index score of 23.1654 points. The continuous rise in labor force absorption indicates that, despite not reaching optimal conditions, there is a significant growth trajectory. The working population increased by 5.18% year on year (YoY) to 459,350 people. This is due to job shifts during the Covid-19 pandemic. In line with this, this is supported by the increasing number of people working in agriculture and industry which increased by 9.16% (YoY) and 36.92% (YoY) respectively compared to August 2019 (LPP Provinsi Papua Barat, 2021). West Papua exhibits a positive economic recovery value of 1.6206, suggesting a rebound following the challenges posed by the coronavirus disease 19 pandemic. This recovery is substantiated by BPS data, which reveals a 5.17% increase in the working population compared to the previous year, totaling 483,681 individuals in 2021 (Badan Pusat Statistik, 2022). The biggest contributor to employment is agriculture, forestry, and fisheries. When assessed against the fourth quarter of 2020, the mining and quarrying industry has shown a notable enhancement in its performance (LPP Provinsi Papua Barat, 2022). The negative resistance-positive recovery groups are the provinces of North Sumatra, West Java, DI Yogyakarta, North Sulawesi, South Sulawesi, and Papua. Papua Province has the lowest resistance index value compared to other provinces with a figure of -22.9598 points. Data from the Bureau of Labor Statistics indicates that the onset of Covid-19 has led to an increase in unemployment, affecting 8,559 individuals. Furthermore, in the year 2020, a total of 216,617 employed resilience experienced a decrease in their working hours as a direct consequence of the pandemic (Badan Pusat Statistik, 2021). This is because companies prefer to implement efficiency by laying off workers who do not have a strategic impact on the company. Papua Province has a positive economic recovery value of 4.733. The increase in the workforce is evident, as the number of employed individuals rose from 1.69 million in 2020 to 1.89 million in 2021 (LPP Provinsi Papua, 2022). The positive resistance-negative recovery groups are Aceh, West Sumatra, Jambi, West Kalimantan, Bengkulu, East Kalimantan, Lampung, South Kalimantan, West Sulawesi, and Central Sulawesi. Micro, small, and medium enterprises (MSMEs) are considered to be resistant in dealing with various previous crises, although the crisis due to Covid-19 is currently putting enormous pressure on them. The growing significance of micro, small, and medium enterprises (MSMEs) is believed to have enabled regions to endure challenging times and subsequently recover, largely due to their substantial contribution to employment. The Aceh recovery index still shows a negative value of -0.97 points. This is because household incomes in Aceh Province are still not diversified so that it has a high risk of exposure to shock. Based on data on the distribution of financing to support regional recovery in Aceh Province, 55.11% is still dominated by consumer loans (LPP Provinsi Aceh, 2022). The negative resistance-negative recovery groups are the provinces of Bali, Bangka Belitung Islands, Gorontalo, Central Java, DKI Jakarta, and East Java. DKI Jakarta has the second lowest resistance index value after Papua and a negative recovery value with respective figures of -16.06 and -0.17 points. Based on data, the working-age population experienced reduced working hours by 35.91%, and 1.66% were recorded as temporarily not working due to the coronavirus disease-2019 pandemic in Jakarta (LPP Provinsi DKI Jakarta, 2021). The shopping centers experienced a temporary shutdown as part of the emergency response measures implemented during the Covid-19 pandemic. The re-opening of shopping malls in Jakarta, which commenced in June 2020, has failed to stimulate a resurgence in the business sector. This lack of progress is largely due to alterations in consumer spending habits, the community's income levels remaining below pre-pandemic standards, and continued restrictions on visitor capacity within the malls.

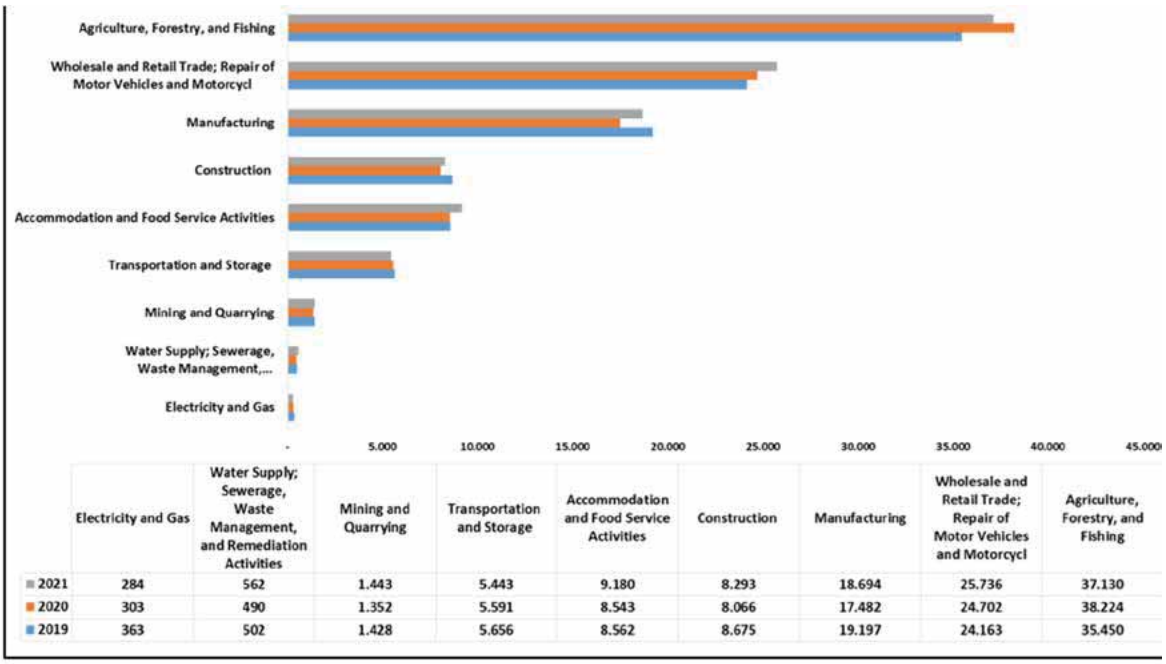
Overall, the stability of employment during the Covid-19 pandemic was enhanced by an uptick in the number of individuals employed in the sectors of agriculture, forestry, and fisheries. According to Fig. 5, these sectors contributed the highest labor absorption compared to others. This significant contribution not only provided employment but also influenced environmental practices in the region. Key determinants of environmental quality included the implementation of sustainable land management strategies and the judicious use of resources, both of which adhered to the tenets of conservation. The pandemic spurred various innovations to stabilize both the economy and the environment, positively impacting labor's influence on the environment. Xaisongkham and Liu (2024) and Bai *et al.* (2021) also

showed that labor can have a positive impact on the environment. According to Bowen and Stern (2010), the 2008-2009 crisis provided opportunities to strengthen environmental policies and initiate green investments for environmental improvement. Bakaki and Bernauer (2018) added that there are still many opportunities to develop environmental policies during economic recessions.

Results of multiple linear regression testing on environmental quality index 2020 and 2021

In Tables 3 and 4, the results of the descriptive statistics are obtained from the dependent and independent variables.

The fundamental assumptions associated with cross-sectional data analysis encompass the normality assessment, the examination of multicollinearity, and



	Electricity and Gas	Water Supply; Sewerage, Waste Management, and Remediation Activities	Mining and Quarrying	Transportation and Storage	Accommodation and Food Service Activities	Construction	Manufacturing	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycl	Agriculture, Forestry, and Fishing
2021	284	562	1.443	5.443	9.180	8.293	18.694	25.736	37.130
2020	303	490	1.352	5.591	8.543	8.066	17.482	24.702	38.224
2019	363	502	1.428	5.656	8.562	8.675	19.197	24.163	35.450

Fig. 5: Spatial distribution of economic resistance in 34 provinces of Indonesia in 2021 (Badan Pusat Statistik, 2022)

Table 3: Description statistics of the EQI 2020 variables

Variable	Mean	Maximum	Minimum	SD
Environmental quality index	71.010	79.750	52.980	5.621
Resistance index	3.341	19.795	-20.518	9.830
Gross regional domestic product growth rate	-1.239	5.350	-9.330	2.412
Information and technologies	38.503	50.635	24.290	5.223
Population	7,947	48.274	701	11.291
Population density	739	15.907	9	2.708
Recovery rate of Covid-19 patients	78.056	92.540	52.510	11.699

Table 4: Description statistics of the EQI 2021 variables

Variable	Mean	Maximum	Minimum	SD
Environmental quality index	72.237	81.800	54.430	5.558
Recovery index	0.195	4.614	-1.474	1.140
Gross regional domestic product growth rate	4.177	16.400	-2.470	3.583
Information and technologies	39.150	52.850	22.665	5.515
Population	8.020	48.782	713	11,377
Population density	744	15.978	9	2.721
Recovery rate of Covid-19 patients	96.708	98.370	91.140	1.629

the evaluation of heteroskedasticity. The normality of the data distribution can be assessed using the Jarque-Bera value. Based on the normality test results in Table 5, all variables have a probabilitas (Prob.) value greater than their significance level (α = 5%), indicating that the data in this study is normally distributed.

The multicollinearity test between variables is presented in Table 6. The tabulated findings demonstrate that multicollinearity is not an issue among the variables, as the variance inflation factor (VIF) values for all variables are less than 10.

Next, the heteroskedasticity test is presented in Table 7. The results show that the Prob. Observation R-squared is greater than the alpha level of 0.05, indicating that this model can predict the observed values accurately.

Table 8 presents the results obtained from the analysis regarding the various factors that influence the environmental quality index.

The estimation results produced the EQI_2020 and EQI_2021 equation models as shown in Eqs. 6 and 7 (Gujarati and Poter, 2009):

$$\mathrm{EQI}_{2020_i} = 101.960 + 0.009\mathrm{RESIS}_i - 0.250\mathrm{LGRDP}_i - 0.204\mathrm{IT}_i - 2.931\mathrm{POP}_i - 5.756\mathrm{PD}_i - 0.005\mathrm{RR}_i \quad (6)$$

$$\mathrm{EQI}_{2021_i} = 137.185 + 0.629\mathrm{RECOV}_i - 0.110\mathrm{LGRDP}_i - 0.158\mathrm{IT}_i - 3.605\mathrm{POP}_i - 5.470\mathrm{PD}_i - 0.347\mathrm{RR}_i \quad (7)$$

According to the findings illustrated in Table 8, the probability of the F-statistic indicates a noteworthy effect. This means that the resistance index, LGRDP, IT, population, population density, and coronavirus disease-2019 recovery rate influence the environmental quality index during the recession. Findings from the EQI_2 estimation reveal that factors such as the recovery index, LGRDP, information technology, demographic variables, population density, and the recovery rate associated with Covid-19 significantly affect the environmental quality index. This confirms the validity of the alternative hypotheses in Eqs.6 and 7 of this study. The R-squared for the EQI_2020 model is 0.7502. This means that the resistance index, LGRDP, IT, population, population density, and Covid-19 recovery rate contribute 75.02% to the environmental quality index, while the remaining 24.98% is influenced by other factors not included in the model. In the 2021 EQI model, the R-squared value is 0.8359, indicating that the recovery index, LGRDP, IT, population, population density, and Covid-19 recovery rate contribute 83.59% to the environmental quality

Table 5: Normality test results on environmental quality index

Test	EQI_2020	EQI_2021
Jarque-Bera	0.7028	1.3327
Prob.	0.7036	0.5135

Table 6: Multicollinearity test results on environmental quality index

Test	Centered VIF EQI_2020	Centered VIF EQI_2021
Resistance index (RESIS)	1.2002	
Recovery index (RECOV)		1.2692
Gross regional domestic product growth rate (LGRDP)	1.5801	1.4068
Information and technologies (IT)	1.8957	1.6741
Population (POP)	2.1207	2.2911
Population density (PD)	2.6352	2.3830
Recovery rate of coronavirus disease-2019 patients (RR)	1.2640	1.3232

Table 7: Heteroskedasticity test results on environmental quality index

Test	EQI_2020	EQI_2021
Observation R-squared	7.4395	5.7137
Prob.	0.2821	0.4560

Table 8: Results of multiple linear regression testing on environmental quality index 2020 and 2021

Test	EQI_2020	EQI_2021
RESIS	-0.0093 (0.0545)	
RECOV		0.6298* (0.3870)
LGRDP	-0.2509 (0.2547)	-0.1109 (0.1297)
IT	-0.2047* (0.1289)	-0.1582** (0.0919)
POP	-2.9317** (1.6118)	-3.6054*** (1.3452)
PD	-5.7561*** (1.1460)	-5.4704*** (0.8765)
RR	-0.0053 (0.046)	-0.3472 (0.2767)
C	101.9601 (7.6035)	137.1854 (28.0474)
Observation	34	34
F-Statistic	17.5226***	29.0229***
R-squared	0.7502	0.8359

Notes: *= Probability value (p-value) less than (<) 0.1; **=p-value<0.05; ***=p-value<0.01; the coefficient of regression is the number that is not in parentheses; Standard Eeror (SE) in parentheses

index, while the remaining 16.41% is influenced by other factors not included in the model. According to the initial results of the calculations, the resistance index failed to demonstrate a statistically significant impact on the EQI. The outbreak of the Covid-19 caused a decrease in the labor force in eight out of nine economic sectors within Indonesia. The determined resistance index demonstrated an inconsistent level of resilience throughout the 34 provinces in Indonesia (Fig. 3). Provinces that were categorized as resistant to the Covid-19 shock were characterized by an increase in the workforce in the agriculture, plantation, and fisheries sectors (Badan Pusat Statistik, 2021). The expansion of the workforce did not lead to an enhancement in the EQI. While there was a rise in the EQI in 2020, this improvement was not evenly spread across different regions. Significant contributions to greenhouse gas emissions arise from the agriculture, plantation, and fisheries sectors (KLHK, 2022). These findings support the neoclassical economic theory, which posits that changes in economic variables, such as employment, do not directly influence the environment. This analysis clarifies that the incongruence between employment resilience and the progress of the EQI caused the resistance index to have an insignificant effect on the EQI. This finding aligns with the studies by Wang and Li (2021) and Adesina and Muteba Mwamba (2019) which also found no significant influence of the employment on the EQI. Given the constraints of the data utilized in this study, an investigation incorporating long-term data may enable the employment resistance index to exert a substantial influence on environmental sustainability over an extended period. In contrast to 2020, during the Covid-19 recovery period in 2021, the recovery index showed a positive impact on the EQI. Each one-point increase in the recovery index was associated with a 0.6298-point increase in the EQI during the Covid-19 recovery period. The economic downturn resulting from the Covid-19 necessitated the emergence of numerous innovations in economic activities, which were specifically designed to improve efficiency and decrease social contact, thereby curtailing the potential spread of the virus. Data shows that the workforce increased by 2.6 million in 2021. This increase was in line with the EQI, which grew to 72.24 in 2021. The increase in the workforce led to better environmental conditions, positively affecting the environmental quality index. This aligns with the research by Xaisongkham and Liu (2024) and Bai *et al.* (2021), which explains that the employment positively impacts EQI. The GRDP growth rate did not show a significant impact on EQI during the 2020

recession and the 2021 recovery period. In Indonesia, the Agriculture, Forestry, and Fisheries sectors continue to play a pivotal role in the economy, representing 40% of the GDP in 2020 and experiencing a slight decline to 38.8% in 2021 (Badan Pusat Statistik, 2021). The EKC mechanism is less effective in explaining the growth-environment relationship in resource-dependent countries. The EKC theory may not fully apply to guide Indonesia's environmental and economic policies. Badeeb *et al.* (2020) added that resource-based countries do not follow the EKC pattern. The findings of this research substantiate the natural resource curse (NRC) paradox, which posits that a state's reliance on natural resources for revenue does not inherently lead to successful sustainable development (Rahma *et al.,* 2021). This aligns with research by Uddin (2021) and Arnaut and Lidman (2021) which also found no correlation between GDP and environmental quality. These findings emphasize the need to reconsider sustainable development strategies. It is essential for forthcoming policies to emphasize economic advancement that encourages sustainable methodologies in leading sectors such as agriculture, forestry, and fisheries. To diminish dependence on natural resources in the aftermath of the pandemic, it is essential to pursue investments in green technology alongside efforts to diversify the economy. The percentage of technology and information showed a significant negative impact on EQI during the 2020 recession caused by Covid-19 and the 2021 recovery period. Each one-percent increase in IT was associated with a 0.2047-point decrease in EQI during the recession and a 0.1582-point decrease in EQI during the Covid-19 recovery period. The rising proportion of the population in Indonesia that possesses mobile phones and computers, along with their access to the internet, has led to a heightened demand for electricity. Power generation in Indonesia is still predominantly fueled by fossil sources such as coal as the primary energy sources. This reliance on fossil fuels has led to IT contributing negatively to the EQI. This study's outcomes lend credence to the Jevons Paradox, which posits that despite the numerous benefits associated with technological advancements, such progress can inadvertently exacerbate environmental degradation through increased electricity consumption in fossil fuel-dependent regions. This finding also aligns with the studies by Awad and Saadaoui Mallek (2023) and Esquivias *et al.* (2022), which indicate that IT has a detrimental impact on the environment. The results indicate that population negatively affected the EQI during both the recession and recovery periods caused by Covid-19. For every additional person in the population, there was a notable decrease of 2.9317 points in the EQI throughout the recession, and a more pronounced decrease of 3.6054 points in EQI was observed during the recovery period following the Covid-19. Overall, the highest population in Indonesia is Java Island, with more than 56% of the total population, followed by Sumatra Island with over 21% in 2020 and 2021. The significant population in Java contributes to an escalated need for land, prompting the conversion of forested areas into developed regions and other infrastructural projects. Data shows that the low EQI in Java is due to the low LQI indicator, which falls into the "poor" category, with an average score of 37.46 points (KLHK, 2022). The low LQI in the Java Ecoregion is due to the disproportionate balance between vegetated land and built-up areas. This situation is evident in Sumatra and other parts of Indonesia, where the rise in population is a significant factor in the degradation of environmental conditions. Data shows that the population increased by 2.478 million people during the coronavirus disease-2019 recovery period in 2021, which could put additional pressure on environmental quality in Indonesia (Badan Pusat Statistik, 2022). This aligns with the research by Woodard *et al.* (2019) and Sharif *et al.* (2023), which also found that population negatively impacts the environment. Population density during the coronavirus disease2019 recession also negatively affected the EQI. During the recession linked to the Covid-19, each additional person per square kilometer in population density was found to be associated with a decline of 5.7561 points in the EQI. Regions with high population density require large resources, which in turn can increase waste and pollution. In spite of the lockdown policies enacted during the Covid-19, consumption remained ongoing throughout the pandemic period. Plastic waste in Indonesia has shown an increase during the Covid-19 pandemic (Herdiansyah and Nuraeni, 2024). Parashar and Hait (2020), also added that online shopping increased during coronavirus disease-2019, leading to a rise in plastic waste used in packaging goods and food

purchased online. During the recovery period from the Covid-19, an increase in population density was found to adversely impact the EQI. Notably, each additional person per square kilometer correlated with a reduction of 5.4704 points in the EQI. This aligns with the research by Aida *et al.* (2022) and Ghezelbash *et al.* (2024), which state that regions with high population density face greater challenges in maintaining environmental quality. The high or low recovery rate of Covid-19 patients did not directly contribute to the EQI in Indonesia. The high or low recovery rate of Covid-19 patients did not directly contribute to the EQI in Indonesia. This is consistent with the findings by Wang and Su (2020), who stated that Covid-19 patient cases do not directly affect the environment. Mkono *et al.* (2022) added that people affected by coronavirus disease-2019 were less likely to consider environmental aspects.

CONCLUSION

Based on the research results, it can be concluded that the spatial distribution of EQI in 2020 and 2021 showed improvement. Data indicates that Indonesia's EQI increased from 66.55 in 2019 to 70.27 in 2020 and 71.41 in 2021. The rise in the environmental quality index was not uniformly experienced throughout all regions of Indonesia. Java Island still has the lowest EQI values and shows figures below the national average. The low EQI values in Java were caused by the high population, leading to an imbalance between vegetated land and built-up land. Second, the recession generated diverse reactions throughout the various geographical areas of Indonesia. According to its classification, a significant number of provinces in Indonesia are identified as belonging to the category characterized by favorable economic resilience and recovery metrics. West Papua had the highest level of resistance compared to other provinces, with the largest contributors to employment being the agriculture, fisheries, and forestry sectors. The majority of provinces exhibiting negative recovery and resistance groups are located on Java Island. DKI Jakarta ranks second lowest in terms of resistance index value, following Papua. This is due to the reduction in working hours and unemployment due to the Covid-19 shock. The reestablishment of malls in Jakarta has not effectively contributed to economic revitalization, as it is hindered by inconsistent household income levels, shifts in consumption trends, and ongoing restrictions on visitor capacity within these retail spaces. The third conclusion indicates that the resistance index, GRDP growth rate, IT, population, population density, and the Covid-19 recovery rate influence the environmental quality index during the recession with a contribution of 75.02%. Partially, the impact of IT on EQI is -0.204 points. The reliance on non-renewable energy sources to operate phones and the internet negatively affects EQI. The impact of population on EQI is -2.931 points. The rising population has heightened the demand for land, resulting in significant environmental degradation. The impact of population density on EQI is -5.756 points. Areas with high population density require more resources, leading to increased waste and pollution. The environmental quality index was not influenced by several other variables, including the resistance index, the growth rate of GRDP, and the recovery rate of individuals affected by Covid-19. The fourth conclusion indicates that the recovery index, GRDP growth rate, IT, population, population density, and the Covid-19 recovery rate influence the environmental quality index during the recovery period from the Covid-19 recession, with a contribution of 83.59%. Partially, the impact of the recovery index on EQI is 0.629 points. As a result of the Covid-19, the recovery period served as a catalyst for the public to pursue a range of innovative approaches to improve the efficiency of economic activities.. Data also shows an increase in the workforce accompanied by an increase in EQI in 2021. The impact of IT on EQI is -0.158 points, while the impact of population is -3.605 points, and population density is -5.470 points. During the recovery period, the findings related to technology and information, alongside population and population density, reflected trends that were consistent with the estimates established during the onset of the Covid-19 crisis. Other variables that did not show an impact on the environmental quality index include the GRDP growth rate and the coronavirus disease-2019 patient recovery rate. The findings of this research are expected to make a significant contribution to the fields of environmental and economic studies. Indonesia's vision to achieve net-zero emissions by 2060 is a concrete step toward sustainable growth. Nonetheless, issues such as economic disturbances, significant rates of land conversion, and reliance on non-renewable energy sources emphasize the critical need for enhanced

policies to effectively confront future challenges. The recommended policies for the government include sustainable natural resource management through the implementation of binding laws in each region. The government should also collaborate with the private sector to support green infrastructure investment in Indonesia. Diversification and expansion of employment in the renewable energy sector should also be enhanced to build economic resilience against recessions. The government must take measures to regulate population growth and density by refining family planning strategies and implementing controlled migration policies. Future researchers are encouraged to enhance theoretical and empirical studies by incorporating current issues and expanding the scope of discussions. It is expected that other elements, such as investment, taxation, and governmental policies, will contribute significantly to the relevant academic discourse. Future research should also explore the relationship between employment resilience and other factors affecting the environmental quality Index over longer periods to better understand long-term impacts and dynamics.

AUTHOR CONTRIBUTIONS

D.O. Ayuningsih conceptualised the central research idea, designed the research, wrote and revised the article. L. Hakim provided the theoretical framework, revisions, supervised research progress and approved the article submissionand. A. Suryantoro helped in the literature review, revisions, supervised research progress and approved the article submission. I. Mafruhah helped in the literature review and improvement of the manuscript. S. Hassan reviewed and improvement of the manuscript. E. Gravitiani reviewed and prepared the maps. N.Q. Fathoni provided the designed the research and collected data. A.I. Hakim helped in improvement of the manuscript.

ACKNOWLEDGEMENT

The authors would like to thank Universitas Sebelas Maret as a forum for studying. Authors extend their gratitude to various parties for critical comments on 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

©2024 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
BPS	Central bureau of statistics
CO_2	carbon dioxide
COVID-19	Coronavirus disease 2019
EKC	Environmental kuznets curve
Eq.	Equation
EQI	Environmental quality index
Fig.	Figure
GDP	Gross domestic product
GRDP	Gross regional domestic product
IT	Information and technologies
LGRDP	Gross regional domestic product growth rate
LQI	Land quality index

MSMEs	Micro, small, and medium enterprises
NRC	Natural resource curse
PD	Population density
PPE	Personnel protective equipment
PPKM	Emergency public activity restrictions
POP	Population
Prob.	Probability
RECOV	Recovery index
RESIS	Resistance index
RR	Recovery rate of coronavirus disease-2019 patients
SD	Standard deviation
SE	Standard error
VIF	Variance inflation factor
YoY	year on year

REFERENCES

Abu-Qdais, H.A.; Al-Ghazo, M.A.; Al-Ghazo, E.M., (2020). Statistical analysis and characteristics of hospital medical waste under novel coronavirus outbreak. Global J. Environ. Sci. Manage., 6(SI): 21-30 **(10 pages)**.

Adesina, K.S.; Muteba Mwamba, J.W., (2019). Does economic freedom matter for CO2 emissions? lessons from Africa. J. Dev. Areas. 53(3): 155-167 **(13 pages).**

Aida, N.; Hermawan, E.; Ciptawaty, U., (2022). The effect of GRDP, foreign invesment and population density on environmental quality in Java Island (2010-2019). In ICEBE, 4th. International conference of economics, business, and entrepreneurship. Lampung, Indonesia.

Alnour, M.; Ali, M.; Abdalla, A.; Abdelrahman, R.; Khalil, H., (2022). How do urban population growth, hydropower consumption and natural resources rent shape environmental quality in Sudan?. World Dev. Sustainability. 1: 100029 **(16 pages).**

Amar, S.; Satrianto A.; Ariusni.; Ikhsan, A.; Siregar, E.S., (2024). Environmental quality and macroeconomic phenomenon. Global J. Environ. Sci. Manage., 10(2): 791-804 **(14 pages).**

Arnaut, J.; Lidman, J., (2021). Environmental sustainability and economic growth in greenland: Testing the environmental kuznets curve. Sustainability. 13(3): 1–14 **(13 pages).**

Awad, A.; Saadaoui Mallek, R., (2023). Globalisation's impact on the environment's quality: Does the proliferation of information and communication technologies services matter? An empirical exploration. Environ. Dev., 45(2022): 100806 **(17 pages).**

Badan Pusat Statistik, (2021). Keadaan Angkatan Kerja Di Indonesia 2021. Badan Pusat Statistik. **(297 pages).**

Badan Pusat Statistik, (2022). Statistik Indonesia 2022. Badan Pusat Statistik. **(828 pages).**

Badeeb, R.A.; Lean, H.H.; Shahbaz, M., (2020). Are too many natural resources to blame for the shape of the environmental kuznets curve in resource-based economies? Resour. Policy. 68(2019): 101694 **(21 pages).**

Bai, S.; Zhang, B.; Ning, Y.; Wang, Y., (2021). Comprehensive analysis of carbon emissions, economic growth, and employment from the perspective of industrial restructuring: a case study of China. Environ. Sci. Pollut. Res., 28: 50767–50789 **(36 pages).**

Bakaki, Z.; Bernauer, T., (2018). Do economic conditions affect public support for environmental policy?. J. Cleaner Prod. 195: 66-78 **(13 pages)**.

Bowen, A.; Stern, N., (2010). Environmental policy and the economic downturn. CCCEP. (18):22 **(29 pages)**.

Butarbutar, P.F.; Ananda, C.F.; Prasetya, F., (2023). The Determinants of environmental quality in Indonesia. J. Indones. Appl. Econ., 11(1): 27–39 **(13 pages).**

Cainelli, G.; Ganau, R.; Modica, M., (2019). Industrial relatedness and regional resilience in the European Union. Pap. Reg. Sci., 98(2): 755–778 **(24 pages).**

Caraka, R.E.; Lee, Y.; Kurniawan, R.; Herliansyah, R.; Kaban, P.A.; Nasution, B.I.; Gio, P.U.; Chen, R.C.; Toharudin, T.; Pardamean, B., (2020). Impact of COVID-19 large scale restriction on environment and economy in Indonesia. Global J. Environ. Sci. Manage., 6(SI): 65-84 **(20 pages)**.

Ekonomou, G.; Halkos, G., (2023). Exploring the Impact of economic growth on the environment: an overview of trends and developments. Energy. 16(11): 1–19 **(19 pages).**

Esquivias, M.A.; Sugiharti, L.; Rohmawati, H.; Rojas, O.; Sethi, N., (2022). Nexus between technological Innovation, renewable energy, and human capital on the environmental sustainability in emerging Asian economies: A panel quantile regression approach. Energy. 15(7): 2451 **(16 pages).**

Ezcurra, R.; Rios, V., (2019). Quality of government and regional resilience in the European Union. Evidence from the great recession. Pap. Reg. Sci., 98(3): 1267–1290 **(24 pages).**

Farajnezhad, M.; Seong Kuan, J.S.T.; Kamyab, H., (2024). Impact of economic, social, and environmental factors on electric vehicle adoption: A review. EIDOS. 17(24): 39-62 **(24 pages).**

Firmansyah, Y.W.; Fathan Fuadi, M.; Sugiester S.F.; Widyantoro, W.; Fadli Ramadhansyah, M., (2021). Environmental conditions and COVID-19 incident. J. Health Sci. Prev., 5(1): 58–64 **(7 pages).**

Fremstad, A.; Paul, M.; Underwood, A., (2019). Work hours and CO_2 emissions: Evidence from U.S. households. Rev. Polit. Econ., 31(1): 42–59 **(18 pages).**

Ghezelbash, A.; Liu, J.; Fahimifard, S.H.; Khaligh, V., (2024). Exploring the influence of the digital economy on energy, economic, and environmental resilience: A multinational study across varied carbon emission groups. Sustainability. 16(7): 2993 **(22 pages).**

Girdhar, A.; Kapur, H.; Kumar, V.; Kaur, M.; Singh, D.; Damasevicius, R., (2021). Effect of COVID-19 outbreak on urban health and environment. Air Qual. Atmos. Health. 14(3): 389–397 **(9 pages).**

Gujarati, D.N.; Porter, D.C., (2009). Basic econometrics fifth edition. McGraw Hill Series. **(946 pages)**.

Gupta, N.; Tomar, A.; Kumar, V., (2020). The effect of COVID-19 lockdown on the air environment in India. Global J. Environ. Sci. Manage., 6(SI): 31-40 **(10 pages)**.

Herdiansyah, H.; Nuraeni, (2024). Environmental awareness and plastic use behavior during the COVID-19 pandemic. Global J. Environ. Sci. Manage., 10(2): 419-434 **(16 pages)**.

Kamyab, H.; Naderipour, A.; Jahannoush, M.; Abdullah, A.; Marzbali, M.H., (2022). Potential effect of SARS-CoV-2 on solar energy generation: Environmental dynamics and implications. Sustainable Energy Technol. Assess., 13(3): 1–14 **(6 pages).**

KLHK, (2021). Laporan indeks kualitas lingkungan hidup Indonesia.

Kementrian Lingkungan Hidup dan Kehutanan. **(71 pages).**
KLHK, (2022). Status lingkungan hidup Indonesia. Kementrian Lingkungan Hidup dan Kehutanan. **(250 pages).**
Khalid, U.; Okafor, L.E.; Burzynska, K., (2021). Does the size of the tourism sector influence the economic policy response to the COVID-19 pandemic? Curr. Issues in Tourism. 24(19): 2801–2820 **(21 pages).**
LPP Provinsi Aceh, (2022). Laporan perekonomian Provinsi Aceh. Bank Indonesia. **(85 pages).**
LPP Provinsi DKI Jakarta, (2021). Laporan perekonomian Provinsi DKI Jakarta. Bank Indonesia. **(133 pages).**
LPP Provinsi Papua, (2022). Laporan perekonomian Provinsi Papua. Bank Indonesia. **(105 pages).**
LPP Provinsi Papua Barat, (2021). Laporan perekonomian Provinsi Papua Barat. Bank Indonesia. **(112 pages).**
LPP Provinsi Papua Barat, (2022). Laporan perekonomian Provinsi Papua Barat. Bank Indonesia. **(68 pages).**
Martin, R.; Sunley, P.; Gardiner, B.; Tyler, P., (2016). How regions react to recessions: resilience and the role of economic structure. Reg. Stud., 50(4): 561–585 **(26 pages).**
Masum, M.H.; Pal, S.K., (2020). Statistical evaluation of selected air quality parameters influenced by COVID-19 lockdown. Global J. Environ. Sci. Manage., 6(SI): 85-94 **(10 Pages)**.
Mkono, M.; Hughes, K.; McKercher, B., (2022). Does the environment matter in the 'new normal'?. Ann. Tourism Res. Empirical Insights. 3(2): 100060 **(3 pages).**
Norouzi, N.; Bashashjafariabadi, Z., (2021). Covid-19 and the environment: challenges and opportunities. Res. J. Ecol. Sci., 1(1): 39–51 **(13 pages).**
Parashar, N.; Hait, S., (2021). Plastics in the time of COVID-19 pandemic: Protector or polluter?. Sci. Total Environ., 759: 144274 **(16 pages).**
Praveena, S.M.; Aris, A.Z., (2021). The impacts of COVID-19 on the environmental sustainability: a perspective from the Southeast Asian region. Environ. Sci. Pollut. Res., 28(45): 63829–63836 **(8 pages).**
Rahma, H.; Fauzi, A.; Juanda, B.; Widjojanto, B., (2021). Fenomena natural resource curse dalam pembangunan wilayah di Indonesia. JEPI., 21(2): 148–163. **(17 pages).**
Rahman, M.M.; Alam, K.; Velayutham, E., (2022). Reduction of CO2 emissions: The role of renewable energy, technological innovation and export quality. Energy Rep., 8: 2793–2805 **(13 pages).**
Rupani, P.F.; Nilashi, M.; Abumalloh, R.A.; Asadi, S.; Samad, S.; Wang, S., (2020). Coronavirus pandemic (COVID-19) and its natural environmental impacts. Int. J. Environ. Sci. Technol., 17(11): 4655–4666 **(12 pages).**
Rushayati, S.B.; Hermawan, R.; Setiawan, Y.; Wijayanto, A.K.; Prasetyo, L.B.; Permatasari, P.A., (2020). The effect of utilization patterns of green open space on the dynamics change of air quality due to the Covid-19 pandemic in Jabodetabek region. J. Nat. Resour. Environ. Manage., 10(4): 559–567 **(9 pages).**
Sharif, A.; Kartal, M.T.; Bekun, F.V.; Pata, U.K.; Foon, C.L.; Kılıç Depren, S., (2023). Role of green technology, environmental taxes, and green energy towards sustainable environment: Insights from sovereign Nordic countries by CS-ARDL approach. Gondwana Res., 117: 194–206 **(13 pages).**
Uddin, M.M.M., (2021). Revisiting the impacts of economic growth on environmental degradation: new evidence from 115 countries. Environ. Ecol. Stat., 28: 153-185 **(33 pages).**
Wang, Q.; Li, L., (2021). The effects of population aging, life expectancy, unemployment rate, population density, per capita GDP, urbanization on per capita carbon emissions. Sustainable Prod. Consumption. 28: 760–774 **(15 pages).**
Wang, Q.; Su, M., (2020). A preliminary assessment of the impact of COVID-19 on environment – A case study of China. Sci. Total Environ., 728: 138915 **(10 pages).**
Wawrzyniak, D.; Doryń, W., (2020). Does the quality of institutions modify the economic growth-carbon dioxide emissions nexus? Evidence from a group of emerging and developing countries. Econ. Res. Ekonomska Istrazivanja. 33(1): 124–144 **(22 pages).**
Woodard, D.L.; Davis, S.J.; Randerson, J.T., (2019). Economic carbon cycle feedbacks may offset additional warming from natural feedbacks. PNAS. 116(3): 759–764 **(6 pages)**.
Xaisongkham, S., Liu, X., (2024). Institutional quality, employment, FDI and environmental degradation in developing countries: evidence from the balanced panel GMM estimator. Int. J. Emerging Markets. 19(7): 1920–1939 **(20 pages)**.
Yunus, A.P.; Masago, Y.; Hijioka, Y., (2020). COVID-19 and surface water quality: Improved lake water quality during the lockdown. Sci. Total Environ., 731: 139012 **(9 pages)**.
Zambrano-monserrate, M.A.; Alejandra, M.; Sanchez-alcalde, L., (2020). Indirect effects of COVID-19 on the environment. Sci. Total Environ., 728: 138813 **(5 pages)**.
Zhong, S.; Su, B., (2021). Assessing the effects of labor market dynamics on CO2 emissions in global value chains. Sci. Total Environ., 768: 144486 **(14 pages)**.

AUTHOR (S) BIOSKETCHES

Ayuningsih, D.O., M.E. Student, Faculty of Economic and Business, Universitas Sebelas Maret, Jl. Ir. Sutami No.36, Jebres, Surakarta, Central Java 57126, Indonesia.
▪ Email: *dyllaoktavia52@gmail.com*
▪ ORCID: 0009-0009-3705-5885
▪ Web of Science ResearcherID: GSJ-0913-2022
▪ Scopus Author ID: NA
▪ Homepage: https://feb.uns.ac.id/feb/

Hakim, L., Ph.D., Instructor, [1]Faculty of Economic and Business, Universitas Sebelas Maret, Jl. Ir. Sutami No.36, Jebres, Surakarta, Central Java 57126, Indonesia. [2]Albert-Einstein-Straße 42-46, Postdam, Germany.
▪ Email: *lukmanhakim@staff.uns.ac.id*
▪ ORCID: 0009-0004-4523-2056
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57209031943
▪ Homepage: https://feb.uns.ac.id/feb/

AUTHOR (S) BIOSKETCHES

Suryantoro, A., Ph.D., Instructor, Faculty of Economic and Business, Universitas Sebelas Maret, Jl. Ir. Sutami No.36, Jebres, Surakarta, Central Java 57126, Indonesia.
- Email: *agustinus_s59@staff.uns.ac.id*
- ORCID: 0009-0002-2890-7256
- Web of Science ResearcherID: NA
- Scopus Author ID: 57191861509
- Homepage: https://feb.uns.ac.id/feb/

Mafruhah, I., Ph.D., Professor, Faculty of Economic and Business, Universitas Sebelas Maret, Jl. Ir. Sutami No.36, Jebres, Surakarta, Central Java 57126, Indonesia.
- Email: *izzamafruhah_fe@staff.uns.ac.id*
- ORCID: 0000-0001-5572-6712
- Web of Science ResearcherID: NA
- Scopus Author ID: 57195231669
- Homepage: https://feb.uns.ac.id/feb/

Hassan, S., Ph.D., Instructor, The center of Sustainable Inclusive and Development at the Faculty of Economics and Business, Universiti Kebangsaan Malaysia, 43600, Bangi, Malaysia.
- Email: *suzi_h@ukm.edu.my*
- ORCID: 0000-0002-1051-158x
- Web of Science ResearcherID : ABS-7612-2022
- Scopus Author ID: 57199302948
- Homepage: https://ukmsarjana.ukm.my/main/lihat_profil/SzAyNTQ3Mg==

Gravitiani, E., Ph.D., Instructor, Faculty of Economic and Business, Universitas Sebelas Maret, Jl. Ir. Sutami No.36, Jebres, Surakarta, Central Java 57126, Indonesia.
- Email: *evigravitiani_fe@staff.uns.ac.id*
- ORCID: 0000-0002-7075-6060
- Web of Science ResearcherID: NA
- Scopus Author ID: 57192986082
- Homepage: https://feb.uns.ac.id/feb/

Fathoni, N.Q., B.E., Faculty of Economic and Business, Universitas Sebelas Maret, Jl. Ir. Sutami No.36, Jebres, Surakarta, Central Java 57126, Indonesia.
- Email: *qoyyimfathoni@gmail.com*
- ORCID: 0009-0008-8159-5582
- Web of Science ResearcherID: LDE-7776-2024
- Scopus Author ID: NA
- Homepage: https://feb.uns.ac.id/feb/

Hakim, A.I., Ph.D., Candidate, Department of Anthropology and Sociology, Universitas Kebangsaan Malaysia (UKM), 43600, Bangi, Selangor, Malaysia.
- Email: *azinuddinikram006@gmail.com*
- ORCID: 0000-0003-2432-3376
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://www.ukm.my/portalukm/phd/

HOW TO CITE THIS ARTICLE

Ayuningsih, D.O.; Hakim, L.; Suryantoro, A.; Mafruhah, I.; Hassan, S.; Gravitiani, E.; Fathoni, N.Q.; Hakim, A.I., (2024). Environmental quality and employment resilience during the coronavirus disease 2019 recession and recovery. Global J. Environ. Sci. Manage., 10(SI): 71-88.

DOI: 10.22034/gjesm.2024.10.SI.05

URL: https://www.gjesm.net/article_715527.html

Global J. Environ. Sci. Manage. 10(SI): 89-104, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Nine circular strategy approach for the sustainable management of waste in the palm oil industry

S. Suprihatin[1,*], N.S. Indrasti[1], H. Prasetya[2], L. Agustina[3], E. Yulistika[4]

[1] *Department of Agroindustrial Technology, Faculty of Agricultural Engineering and Technology. IPB University, PO Box 220, Bogor, West Java, Indonesia*

[2] *Employment and Regional Development, Research and Innovation Agency, Jl. MH Thamrin, Central Jakarta 10340, Indonesia*

[3] *Agroindustrial Technology Study Program, Faculty of Agriculture, University of Lambung Mangkurat, Kotak Pos, Banjarbaru 70714, Indonesia*

[4] *Agroindustrial Technology Study Program, University of Insan Cita Indonesia, Graha Binakarsa, Jl. H. R. Rasuna Said No.Kav. C-18, South Jakarta, Indonesia*

ARTICLE INFO

Article History:
Received 01 May 2024
Revised 05 August 2024
Accepted 09 September 2024

Keywords:
9Rs principle
Circular economy
Closed loop system
Palm oil industry
Regenerative innovation
Sustainability

ABSTRACT

BACKGROUND AND OBJECTIVES: Only a tiny portion of the fresh palm oil fruit harvested can be converted into oil products. The majority of the harvested produce is discarded, indicating that it has not been utilized to its fullest potential. Applying a nine strategy principle (refuse, rethink, reduce, reuse, repair, renew, remanufacture, repurpose, recycle, and recover), palm oil waste can be converted into valuable products. This study aims to identify and assess potential options for implementing the nine strategy principle (refuse, rethink, reduce, reuse, repair, renew, remanufacture, repurpose, recycle, and recover) circular strategy in the palm oil industry from the perspectives of economic, environmental, and social benefits.

METHODS: Field observations were conducted in three palm oil mills as case studies. Assessment is performed throughout every segment of the palm oil production chain, ranging from oil palm nurseries and palm plantations to the stages of harvesting, transportation, and palm oil processing. The nine strategy principle (refuse, rethink, reduce, reuse, repair, renew, remanufacture, repurpose, recycle, and recover) framework is used to identify implementation options that focus on reducing resource consumption in the production chain (refuse, rethink, reduce, reuse, repair, renew, remanufacture, repurpose, recycle, and recover). Assessing the sustainability of the palm oil industry involves an analysis of three primary advantages: economic, environmental, and social factors.

FINDINGS: The quantity of palm oil waste in the form of palm oil mill effluent is approx. 2.88 tons, empty fruit bunches 1.06 tons, mesocarp fiber 0.60 tons, and palm oil shell 0.33 tons per ton crude palm oil produced. A significant portion of waste is not subjected to optimal management practices. Various effective methods for waste management have been identified as potential solutions. The advancement of these techniques can be implemented at multiple stages within the crude palm oil production chain, encompassing both the cultivation phase and the processing facilities for palm oil. The most potential circularity strategies applied to the palm oil industry can increase the added value of oil palm wastes compared to current management practices. The implementation of the nine strategic principles, refuse, rethink, reduce, reuse, repair, renew, remanufacture, repurpose, recycle, and recover, not only enhances value and benefits but also contributes to a significant decrease in waste disposal and the reliance on primary inputs such as synthetic fertilizers and non-renewable energy.

CONCLUSION: Various products derived from palm oil waste are considered as potential, such as construction materials, particle board, pulp and paper, bioenergy, bio-char/soil amendment, bio-pellets and bio-briquettes, organic fertilizer/compost, animal feed, bioenergy, and electrical energy from biogas, and microalgae-based products. By adopting the nine strategic principles of refuse, rethink, reduce, reuse, repair, renew, remanufacture, repurpose, recycle, and recover, the palm oil industry can make substantial progress towards zero discharge. This framework is instrumental in promoting sustainability and stimulating regenerative innovation in the industry's operational practices.

DOI: 10.22034/gjesm.2024.10.SI.06

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

NUMBER OF REFERENCES
70

NUMBER OF FIGURES
3

NUMBER OF TABLES
5

*Corresponding Author:
Email: *suprihatin@apps.ipb.ac.id*
Phone: +8131 089 5109
ORCID: 0000-0001-9641-8820

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Palm oil (Elaeis guineensis) is among the most productive and efficient crops for producing vegetable oil (Alam *et al.,* 2015). Indonesia is the world's leading producer of palm oil (Bello and Raman, 2017; Yoo *et al.,* 2019). As reported by the Central Statistics Agency of Indonesia, the extent of oil palm plantations has expanded to 15.34 million hectares, while the production output for the year 2022 was recorded at 46.82 million tons (BPS, 2023). The rapid expansion of the palm oil industry plays a crucial role and significantly contributes to Indonesia's economy and the well-being of its people. Nonetheless, this increase in production introduces several environmental challenges, particularly related to the waste generated in solid, liquid, and gaseous forms during the processing of palm oil, which requires appropriate management practices (Ng *et al.,* 2016). Proper palm oil waste management will increase its added value while minimizing its negative environmental impact. The palm oil industry produces the main products of crude palm oil (CPO) and palm kernel oil (PKO). It also produces various wastes in the form of solid waste (empty fruit bunches/EFB, shells, mesocarp fibers, cake, and solid/sludge) (Sukiran *et al.,* 2011), liquid waste (palm oil mill effluent/POME) (Sukiran *et al.,* 2011; Sajjad *et al.,* 2018), and gaseous waste such as methane (CH_4), carbon dioxides (CO_2) and odors. Improper management of these wastes may result in elevated levels of pollution in aquatic environments, a rise in greenhouse gas emissions, as well as issues related to eutrophication, and acidification. On the other hand, palm oil wastes contain various valuable materials, such as organic compounds, nutrients, and minerals essential for the palm oil plant. The adverse effects associated with palm oil management practices have garnered heightened scrutiny from local, national, regional, and international stakeholders. Increasingly, both communities and governmental authorities are expressing heightened concern over the consistent application and enforcement of environmental regulations, compelling participants in the palm oil sector to enhance their waste management strategies. The main obstacle to improving environmental management is the increasing environmental costs. Therefore, there is an urgent need to find a cost-effective environmental management approach (Hwang *et al.,* 2022). The nine principles of the 9Rs strategy serve as a foundational framework for circular economy initiatives, directing design efforts that aim to reduce waste and pollution. This approach emphasizes the conservation of natural resources by maximizing the longevity of products, raw materials, and existing resources, while also prioritizing the utilization of renewable and regenerative. The 9Rs principle approach can be a win-win solution to these environmental and economic problems (Cheah *et al.,* 2023). The 9Rs principle focuses on reducing resource consumption in the production chain (Sihvonen and Ritola, 2015; Kirchherr *et al.,* 2017). The 9Rs concept is an extension of the three strategy (3Rs) concept (Reduce, Reuse, Recycle) and the four strategy (4Rs) concept (Reduce, reuse, recycle, and recover) previously popular in waste management. Compared to the 3Rs and 4Rs strategies, the 9Rs strategy presents distinct benefits, notably through its focus on waste prevention and minimization, alongside its optimization of material and energy resources. This 9Rs principle is divided into three major parts, namely making and using products smarter (refuse (R0), rethink (R1), reduce (R2), extending the life of products (reuse (R3), repair (R4), refurbish (R5), remanufacture (R6), repurpose (R7)), and taking other benefits from existing materials (recycle (R8), recover (R9) (Potting *et al.,* 2017; Bappenas *et al.,* 2022). Recent investigations have achieved substantial developments in the integration of the 9Rs principles within the waste management practices of the palm oil sector. One effective strategy that has emerged is the co-gasification of palm oil waste, notably decanter cake and alum sludge, aimed at generating syngas. The study conducted by Abioye *et al*. (2024) demonstrates that the combination of Response Surface Methodology (RSM) and Artificial Neural Network (ANN) can effectively enhance the production of syngas. The study revealed that the ideal parameters for maximizing syngas production included a temperature of 900 degrees celcius (°C), an air flow rate of 10 mililiter per minute (mL/min), and a particle size of 2 milimeter (mm). These specific conditions resulted in the highest observed concentration of syngas, achieving a carbon monoxide and hydrogen (CO+H2) volume percentage of 39.48 percent (%). This study highlights the capacity for generating additional value by converting palm oil waste into sustainable energy. Furthermore, a further

investigation conducted by Abioye *et al*. (2024b) delves deeper into the utilization of decanter cake waste to manufacture syngas. This study showcases that the co-gasification process has the ability to convert this waste into a valuable energy resource. This study further supports the idea of a 9Rs principles by showcasing how industrial waste may be converted into items that have increased value using cutting-edge technology. The research conducted by Satya *et al*. (2023) underscores the feasible use of microalgae, which are grown in wastewater, to support a bio-circular economy. This study offers useful insights into the possible applications of microalgae in bioremediation and the generation of valuable goods from waste. Specifically, it explores the ability of microalgae to absorb micro-pollutants, including microplastics and heavy metals, which could have significant industrial-scale applications. This implies that the application of biological technology in the handling of palm oil waste could facilitate the progress toward environmental sustainability. Furthermore, the application of biomass waste alongside palm oil mill effluent (POME) in the context of renewable energy generation is an important matter of discussion. Zamri *et al*. (2022) explored the viability of renewable energy initiatives that target the reduction of carbon emissions by substituting coal-fired power stations with biomass and POME-derived energy. In a similar vein, Norrrahim *et al*. (2022) emphasize the utilization of POME in the anaerobic digestion procedure to generate biogas, which can be employed for electricity and heat production. The biogas typically contains methane in the range of 65% to 75%. Khanra *et al*. (2022) conducted research on the bioprocessing of microalgae-produced biopolymers within the framework of a circular bioeconomy. The process of anaerobic digestion applied to palm oil mill effluent (POME) yields biogas that contains methane concentrations between 65% and 75%. Hence, it is suitable for utilization in boilers, engines, turbines, and fuel cells to produce heat and power. Asadpour *et al*. (2021) investigated the use of modified EPB as a cost-effective adsorbent material for treating oil spills. The potential of using palm oil biomass waste for this objective was underscored by the researchers. Evidence from research suggests that the application of oleic acid to oil palm fiber significantly increases its effectiveness in absorbing spilled crude oil. This treatment resulted in a maximum weight gain of 4.32% after 6 hours. In a recent study conducted by Kaniapan *et al*. (2021), the authors examine the difficulties associated with using POME as a viable and environmentally friendly option in the biofuel and bioenergy industry. The research highlights the importance of proficiently managing the residual biomass produced during the palm oil milling process. Ho and Khan, (2020) have performed a study on the utilization of palm oil biomass for bioenergy. The inefficiency of boiler combustion might decrease the calorific value due to the lower density of residue and the small size of biomass particles. Lew *et al*. (2020) conducted a study that emphasizes the potential of vermicomposting EFB based compost. The study showcases how circular waste management can enhance sustainability in the palm oil industry. In conclusion, the research underscores the importance of adopting the 9Rs principles in the managing palm oil waste. This may be achieved by the use of energy conversion technologies, the incorporation of microalgae, and the efficient handling of palm oil mill effluent (POME) and residual biomass. By using several circular solutions, the palm oil industry may effectively achieve sustainable waste management, hence promoting the simultaneous achievement of environmental and economic objectives. The present study adopts a life cycle thinking methodology to identify and analyze potential strategies for the integration of the 9Rs principle in the palm oil industry, focusing on environmental, economic, and social factors. It is anticipated that the outcomes of this study will play a significant role in the further development and execution of the 9Rs principle for waste management in the context of the sustainable oil industry. This study aims to identify and assess potential options for implementing the 9Rs circular strategy in the palm oil industry from the perspectives of economic, environmental, and social benefits. This study was carried out under the management of PT Perkebunan Nusantara IV; an Indonesian state-owned enterprise at three different palm oil mills (POM), in 2024.

MATERIALS AND METHODS

The methodological framework adopted for this study is descriptive in nature, incorporating both qualitative and quantitative elements. Data was collected through a comprehensive literature

Table 1: Profile of the observed palm oil mills

No.	Parameter	Unit	POM X	POM Y	POM Z
1	Location	--	Sumatera Island	Sumatera Island	Java Island
2	POM capacity	Ton FFB/hectare (ha)	45	45	30
3	POM land area	Cubic meter (m^3)	15	80	11
4	Area of Owned Palm Oil Plantation	Ha	5,027	7,664	3,515
5	Average POM Utility	%	70.82	100	70
6	Supply of FFB from Own Plantation	%	40	100	98
7	Supply of FFB from other parties' plantations	%	60	0	2
8	Production rate:				
	• CPO	Tons/year	47,000	66,493	31,042
	• PKO	Tons/year	11,000	12,031	
9	Number of Factory Operating Days per Year	Days/year	328	339	313
10	Average operating hours per day	Hours/day	22	22	22
11	POME management		Methane capture with cover lagoon and methane co-firing	Methane capture with cover lagoon system and methane for electricity production	Anaerobic and aerobic pond systems (no facilities for biogas production)

review (secondary data) and through observational research conducted in the field (primary data). The literature study began with collecting scientific journals, reference books, and other sources on the sustainability of the palm oil industry. A series of recent literature searches were executed employing the following keywords: palm oil industry, effective use of palm oil industry waste, sustainability in the palm oil sector, and the theoretical framework and practical application of the9R principle. The field data collection was conducted through direct observation and in-depth interviews with palm oil industry practitioners to collect data on the palm oil industry system, including raw material and energy consumption, process stages and conditions, production output in the form of primary products (CPO), and wastes. Emphasis was placed on identifying the nature and quantity of waste generated during each stage of the process, alongside an evaluation of the current waste management practices. Field observations were conducted in the time period of January-May 2024 at 3 different POM under the management of PT Perkebunan Nusantara IV (an Indonesian state-owned enterprise). POM X and POM Y are located on Sumatera Island, whereas POM Z is located on Java Island. The criteria for choosing the palm oil mills for this study are grounded in the disparities observed in the implementation of waste management strategies, particularly concerning the managing liquid POME. This is very relevance to the aim of this research, namely identifying and assessing the potential for implementing 9Rs, especially in term of bioenergy and nutrients recoveries. Table 1 presents a concise overview of the three palm oil mills that were examined. Palm oil mills X, Y, and Z have an installed production capacity of 45, 45, and 30 tonnes of fresh fruit bunches per hour (FFB/h). The three palm oil mills have differences in POME management. POM Y also manages its POME anaerobic system and produces biogas (methane) as a source of electrical energy. POM Z manages its POME in a conventional way, namely a series of anaerobic and aerobic ponds

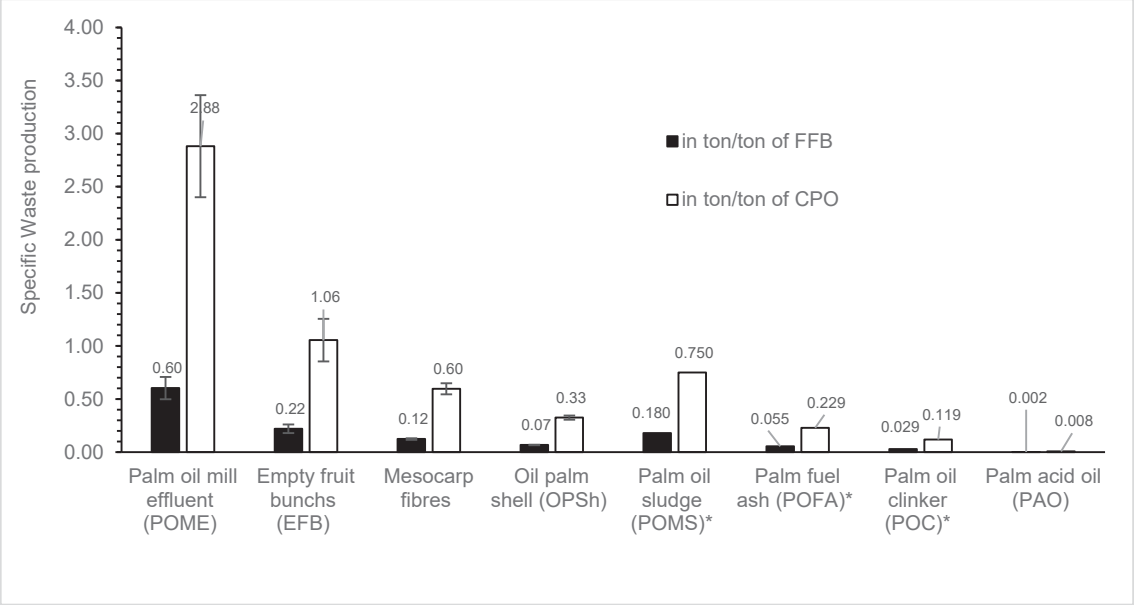


Fig. 1: Specific production of various oil palm waste (Source: Processed from observed POM and (*) data from Liew *et al.,* 2016)

(ponding system). The processed POME is then discharged into the river.

The process of identifying opportunities for the application of the 9Rs principle occurs at every phase of the CPO production chain, involving an analysis of the feasibility of integrating the 9Rs principle within various circularity strategy alternatives. The analysis is carried out at each stage in the CPO production chain, starting from oil palm nurseries, oil palm plantations, harvesting, transportation, and oil palm processing. Moreover, at the oil palm processing stage in the palm oil mill, an in-depth assessment is performed to explore the potential application of the 9Rs principle within the mill's operational system. This assessment covers several components, including the input phase, which addresses the treatment of raw and additional materials; the processing phase, which involves the management of loose fruit from the bunch, sterilization or boiling, and pressing; and the output phase, which focuses on the main products, namely crude palm oil (CPO), palm kernel oil (PKO), and the by-products or waste produced. Identification and analysis of opportunities for implementing 9Rs principle are carried out using the circularity strategy approach (R0, R1, R2, R3, R4, R5, R6, R7, R8, and R9) at each CPO production chain. An elevated R number signifies a heightened demand for essential technological advancements, which also implies a proximity to linear economic methodologies. Conversely, a lower R number indicates a greater alignment with circular economic practices. The literature provides accessible definitions for each of these R terms (Potting *et al.,* 2017). Each prospective possible 9Rs principle application is assessed by considering economic, environmental, and social aspectsThe economic dimensions are examined through the assessment of costs and benefits as documented in existing literature. Environmental aspects are reviewed, including the type of solid waste (pollutants), liquid, and gas waste formed during the CPO production process. A qualitative analysis of social factors is undertaken, focusing on employment opportunities and additional social benefits.

RESULTS AND DISCUSSION

Types, characteristics, and potential utilization of palm oil waste

In the palm oil industry, the manufacturing process results in the generation of by-products or waste, which can be classified into solid, liquid, and gaseous forms. Key waste materials produced during palm oil processing consist of tree trunks, leaf stalks, fibrous residues, solid waste, shells, palm kernel cake, EFB, and the liquid by-product referred to as palm oil mill effluent

(POME). These wastes come from different process stages and have different characteristics, quantities, and uses. Fig. 1. shows the specific waste production from the CPO production process, presented in tons per ton of FFB and tons per ton of CPO. The amount of waste produced does not inherently reflect its value. Several elements contribute to the valuation of a material, including its ability to satisfy user expectations, its presentation in a usable format, its situational appropriateness, its timely availability, and the convenience associated with ownership. Table 2 delineates the various categories of palm oil waste, providing detailed descriptions of their attributes and applications. The generation of each waste type is contingent upon the volume of FFB that are processed. Recording the amount of FFB processed and the amount of CPO produced by palm oil companies is usually better (more complete) than recording the amount of waste production, so with the help of these conversion factors, the production rate of each type of palm oil waste can be estimated for any levels of processing rates of palm oil mills. Additionally, this data proves to be valuable in determining the appropriate size of the processing unit required to utilize or handle the waste generated from the palm oil mill. However, it should be noted that there is variation between palm oil mills in terms of CPO yield; even within a palm oil mill, there is variation in this from time to time. This variation is contingent upon multiple elements, such as the quality of the palm oil plantation, the seasonality of the harvest, the effectiveness of the palm oil mill's operations, and the maintenance and operational methodologies adopted by the mills in question.

Potential application of 9Rs principle in the palm oil industry

The material and energy closed loop is a key factor in the success of the transition to a circular economy. As articulated by the 9Rs principle, this closed cycle is considered the pivotal component of the production and consumption system. It encourages a zero-waste philosophy and the pursuit of zero non-renewable energy consumption. The concept of industrial ecology (Ayres and Ayres, 2002) is often used to realize the closing of the loop, where the output of one component becomes the input of another component so that almost all material flows are cyclical. Resources and waste are frequently not clearly defined, as the byproducts generated by one element of an ecosystem can be utilized as resources by another. In systems that predominantly incorporate inputs from photosynthetic processes and chemical synthesis, this relationship promotes a zero-waste paradigm and significantly reduces the need for primary material input. The industrial framework incorporates numerous processes, economic limitations, and environmental, health, and safety considerations for optimal resource utilization (Basu *et al.,* 2006). Within the palm oil industry, it is feasible to attain an "energy-independent" model. The practices of waste reuse and recycling are essential components in fostering a closed-cycle industrial ecosystem. A perfectly closed system means no waste, material, or energy input (Bantacut and Novitasari, 2016). This study covers all types of palm oil waste (Plantation and POM) and uses a life cycle thinking approach and applies the 9Rs strategy. In relation to the CPO production system, Fig. 2 depicts various opportunities for technological intervention that could facilitate the closure of material and energy flow loops, viewed through the lens of the life cycle of crude palm oil production. The CPO production system consists of the sub-systems of plantation nurseries and maintenance, fresh fruit bunches transportation and handling, palm oil processing, produced CPO handling (storage, transportation, and use), and handling and utilization of palm oil wastes. Various types of palm oil waste can be reduced, reused, recycled, or recovered for material and energy. Furthermore, the principles of refuse and rethink hold significant potential for application, especially in relation to the employment of non-renewable, toxic, and environmentally harmful materials and energy inputs. In each of these production chains, various opportunities have been identified for potential implementing circularity strategies, as presented in Table 3.

As described above, palm oil waste varies greatly in type, helpful content, and potential to be processed into useful and high-value products. Fig. 3 illustrates a schematic representation of waste utilization within the palm oil industry, which has been recognized as a potential resource. The waste processing products can be reused in palm oil plantations, in POM, or for other purposes outside the crude palm oil production system. Consequently, the result of one stage in the process serves as the input for the subsequent stage, ensuring that all outputs are not classified as waste, thereby fostering the development of a zero-waste industry.

The implementation and execution of a 9Rs principle

Table 2: Types and characteristics of oil palm wastes and potential products derived from the wastes

No.	Type	Description
1	Tree trunks, leaf sheaths, and oil palm leaves	Oil palm tree trunks and fronds are vegetative parts of the plant that are usually pruned during plantation maintenance. This type of waste is characterized by its content of protein, fat, and lignin, making it suitable for utilization as raw materials in the creation of compost, fuel sources, construction materials, and primary ingredients for the production of cellulose-derived products, including particle board. Oil palm fronds and leaves can also be used as animal feed, which supports the integration of oil palm plantations with cattle farms.
2	Mesocarp fibres	The mesocarp, or fruit flesh, of the oil palm serves as the source of fiber, which is obtained subsequent to the oil extraction process.. This fiber is rich in cellulose and lignin. Fiber production is around 13% of the processed FFB. Fiber has been used as boiler fuel in palm oil mills, as raw materials for fiber-based products such as particle boards and organic polybags, and as material for mulch in oil palm plantations.
3	Solid	Solid is a solid residue produced from the processing of crude palm oil. Solid contains fiber and residual oil. Solid/sludge production is around 2.5% of processed FFB. Solid and sludge components can be effectively employed as essential materials in the processes of compost generation and animal feed production.
4	Palm oil shell	Palm oil shells consist of multifaceted layers that envelop the seeds of the oil palm. They are produced as a byproduct of the processing of palm kernels. Shell production is around 5.5-7% of processed FFB. These shells are highly calorific and have been used as boiler fuel. Shells can be used as raw material to produce activated charcoal and liquid smoke.
5	Palm kernel meal/cake	Palm kernel meal is a by-product of the extraction process of palm karnel oil. Kernel cake production is around 3% of processed FFB. The nutritional value of cake makes it an appropriate option for animal feed. Additionally, it can be utilized as a fundamental component in the creation of compost.
6	EFB	Empty Palm Fruit Bunches are the remaining fruit bunches after the fruit is picked and the oil is extracted. The empty fruit bunches possess a significant amount of fiber. The production of EFB is around 21-22% of the processed EFB. EFB is used as boiler fuel, raw material for compost production, planting media, or used as mulch. EFB can be used as a primary material for making fiber-based products (paper pulp), raw material for biochar and bio-oil (Chang, 2014; Parthasarathy *et al.,* 2024), and soil amendment.
7	POME	POME is liquid waste produced from the palm% oil processing, which amounts to around 60-67% of the processed FFB. It contains organic matter biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), color, turbidity, nutrients, minerals, and residual oil in high concentrations. POME contains mostly water (95-96%), oil (0.6–0.7%), Total Solids (4-5%), and TSS (2–4%) (Irvan, 2018). POME represents a significant challenge within the environmental oversight of the palm oil sector, primarily due to its substantial volume and the complexities associated with its treatment. Traditionally, POMs use POME as a source of water and nutrients on oil palm plantations (land application) after pre-treating. POME can be processed through an anaerobic fermentation process to produce biogas which is used as a renewable energy source in the form of biogas for power plants (POM Y), or as a source of boiler fuel (POM X). The palm oil mills secondary effluent/POMSE can be used as a medium for microalgae cultivation (Baihaqi and Paratama, 2023). Microalgae biomass has the potential to be converted into feed for livestock or used as a feedstock in the production of biodiesel. Furthermore, POMSE can be further processed by electrocoagulation (Sailah *et al.,* 2021) or photocatalytic process (Agustina *et al.,* 2024) to produce recycled water.
8	Palm oil sludge (POMs)	POMs are produced during the liquid waste (POME) processing process, as much as 18% of FFB (Liew *et al.,* 2016). The composition of POMs includes organic materials, essential nutrients, and minerals, indicating their potential application as either feed for livestock or as organic fertilizer.
	Palm fuel ash (POFA)	The burning of mesocarp and kernel produces POFA, as much as 5.5% of FFB (Liew *et al.,* 2016). This ash contains silica which is synthesized into silica nanoparticles (Si-NPs) because its properties are ideal for water purification (Wardanu *et al.,* 2024).
	Palm oil clinker (POC)	POC is a by-product of burning mesocarp fiber and kernel in an incinerator, amounting to about 2.85% of FFB. This rock-like material can be used in cement material mixtures (Liew *et al.,* 2016). In the production of lightweight concrete, POC aggregates served as replacements for traditional coarse and fine aggregates. (Abutaha *et al.,* 2016)
	Palm acid oil (PAO)	POME contains oil residues up to 4,000 mg/L. The remaining oil is recovered and converted into biodiesel or sustainable aviation fuel/ sustainable aviation fuel (SAF) (Ahmad *et al.,* 2003). Mechanical separation of the remaining oil can produce PAO of around 0.18% of FFB.

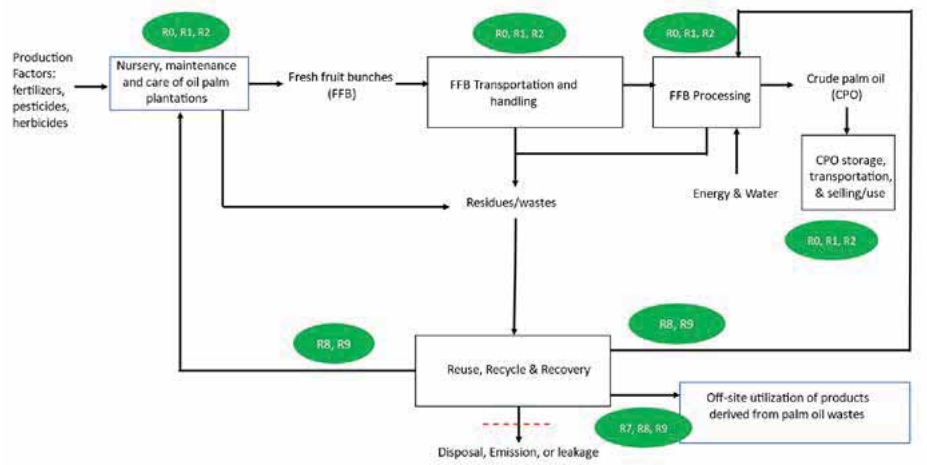


Fig. 2: Possible points for innovation of 9Rs principle in palm oil plantation and processing

Table 3: Potential application of 9Rs strategy in crude palm oil production chain

No.	CPO production process stages	Potential circularity strategies
1	Oil palm plantation nursery and maintenance	• Biofertilizer, organic fertilizer, biopesticide (R0, R1, R2) • Integrated palm oil plantation, agroecology, precision palm oil plantation, semi-organic plantation (R0, R1, R2)
2	FFB transportation and handling	• Green logistics and handling to minimize the FFA forming (R0, R1, R2)
3	FFB Processing	• Cleaner production and lean manufacturing to minimize product loss and resource input (R0, R1, R2)
4	Handling (Storage, transportation and selling/use) of CPO	• Green logistics, storage, and handling to minimize the FFA forming (R0, R1, R2) • Sustainable consumption and sustainable use of CPO (R0, R1, R2)
5	Waste handling and utilization	• Utilization of palm oil waste as raw material for making valuable products (R7) • Recovery of nutrients, organic matter and energy (as organic fertilizer, soil amendment, and bioenergy) (R9) • Recycling palm oil waste, processing, utilization, and waste disposal (R8, R9)

option, as illustrated in Fig. 3 can be carried out at different levels, namely micro-level (a 9Rs principle carried out by one company), meso level (expansion from one company to collaboration between companies through symbiosis or industrial cooperation, and macro-level (implementation on a broader scale, emphasizing efforts made in a region, or country in promoting the adoption of the 9Rs principle paradigm (Bueren *et al.,* 2023). The processing and application of palm oil waste are instrumental in diminishing environmental impacts, yielding economic and social benefits, and lowering the consumption of primary resource inputs. Table 4 shows the analysis results based on principles summarized in the circularity levels R0-R9. This study incorporates an assessment of the waste types, the alternative products that could be generated, a detailed account of the circularity strategy, and the benefits that can be realized. It can be seen that by processing palm oil waste optimally, the value of the circularity level (its R number) is getting smaller, and this means approaching the concept of a higher 9Rs principle and leading to increased value or benefits of materials/energy, and reducing primary inputs such as energy and synthetic fertilizers, as well as reducing the amount of waste disposal. The evaluation of an industry's sustainability is based on three critical

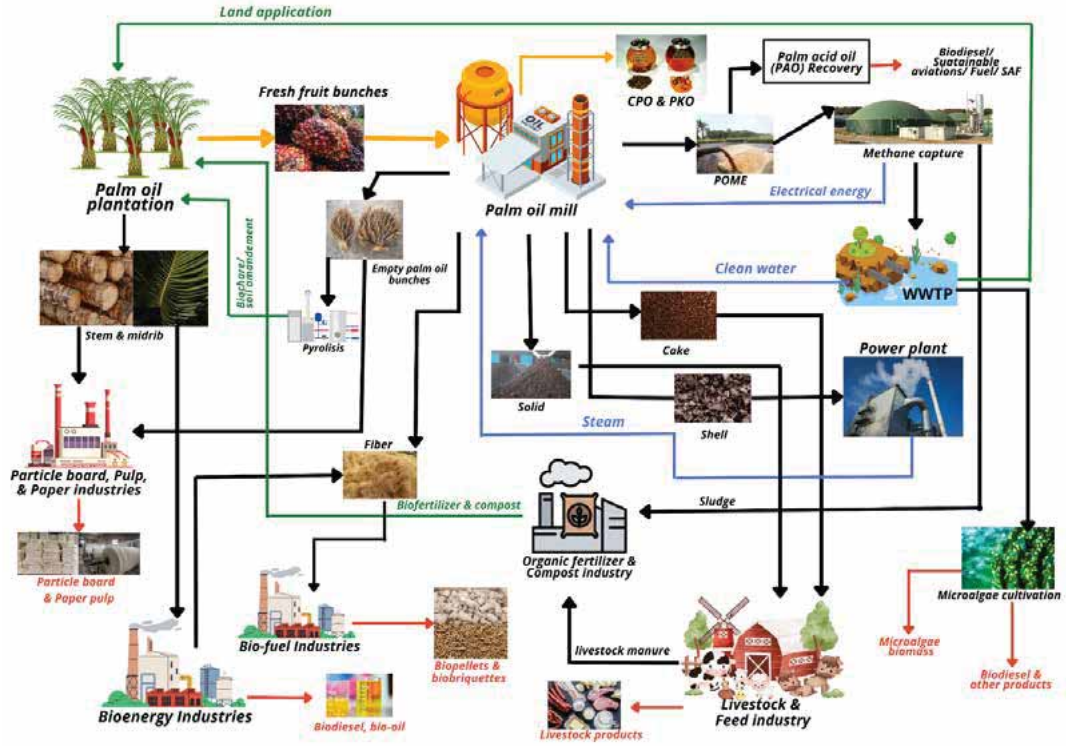


Fig. 3: Scheme of palm oil waste utilization within 9Rs principle

dimensions: economic viability, environmental impact, and social responsibility. To support the sustainability of the palm oil industry, Table 4 also presents the potential application of the 9Rs principle in palm oil waste management with three benefits: economic, environmental, and social. This qualitative evaluation focuses on the potential opportunities and the feasibility of implementation within the palm oil sector.

The various levels of circularity outlined in Table 4 present opportunities for implementation within the palm oil sector, potentially enhancing the value derived from palm oil waste in comparison to existing management strategies. The findings of this study using the 9R approach have not been fully implemented in most palm oil industries, particularly the R0-R2 strategies. Traditionally, the palm oil industry has utilized a waste management framework that emphasizes end-of-pipe practices, which are centered around the treatment and disposal of waste. While some Rs (R7, R8, R9) have been implemented by a few palm oil mills (POMs), others strategies (R0, R1, and R2) still require further introduction to the industry regarding their potential benefits so that the palm oil industry becomes interested in adopting them. Utilizing the 9Rs principle can lead to an increase in value-added processes, a reduction in waste disposal efforts, and a decrease in the utilization of primary materials. This application plays a significant role in the palm oil industry by steering it towards a zero discharge model, enhancing its sustainability, and promoting innovative regenerative practices within the sector. The potential derivative products from palm oil waste include construction materials, particle boards, pulp and paper, bioenergy, and biochar/soil amendment (derived from waste such as oil palm tree trunks, fronds, palm leaves, and EFB, bio-pellets and bio-briquettes (from mesocarp fiber), organic fertilizer/compost (from sludge and boiler ash), animal feed (from palm kernel cake and solids), shells (used as fuel to produce energy/steam in factories), as well as electrical energy from biogas or methane capture, and microalgae-based products (with treated POME as the cultivation medium). By adopting the 9Rs principle in the management of palm oil waste, significant contributions can be made to the three foundational pillars of sustainability: economic, environmental, and

Table. 4: Analysis of opportunities for implementing 9Rs principle for sustainable palm oil waste management

No.	Type of waste	Level R in the product	Benefit
1	Oil palm tree trunk	R7: construction material (Poopalam *et al.,* 2024), particle board (Baskaran *et al.,* 2012; Baskaran *et al.,* 2017), R9: bio-energy/bio-pellets (Mawardi *et al.,* 2023)	• Economic: New income source • Environmental: Reduces waste • Social: Creates jobs.
2	Leaf-sheath	R9: bio-energy/biobriquettes (Putra *et al.,* 2019), R7: zephyr boards (Pambudi *et al.,* 2022)	• Economic: Cost-saving and new source of income • Environmental: Reduces pollution • Social: Job creation and community education.
3	Mesocarp fibres	R7: Organic polybags (Jaya *et al.,* 2020; Karvinaldi *et al.,* 2022), Particle board (Baskaran *et al.,* 2012; Baskaran *et al.,* 2017) R9: bio-energy/bio-pellets (Abdullah *et al.,* 2022)	• Economic: Feasible new business • Environmental: Reduces fiber waste • Social: New employment opportunities.
4	Solid decanter	R8: animal feed (Ramon *et al.,* 2022), Organic fertilizer, soil improver, or compost.	• Economic: Saves costs for livestock feed and fertilizers • Environmental: Reduces waste and environmental pollution • Social: Educates community.
5	Palm oil shell	R9: Bio-fuel (Setiawan, 2016; Kaniapan *et al.,* 2021; Yanti *et al.,* 2023), R7: liquid smoke (Ginayati *et al.,* 2015)	• Economic: Saves energy costs • Environmental: Reduces shell waste • Social: Job creation and positive perception.
6	Palm kernel meal/cake	R8: animal feed, organic fertilizer (Harahap *et al.,* 2023)	• Economic: New income and sabe fertilizer cost • Environmental: Reduces pollution • Social: New jobs and community education.
7	EFB	R7: particle board (Dewi *et al.,* 2019; Raharjo, 2020), pulp/paper, Planting media for oyster mushrooms (Sulistiawati *et al.,* 2017) R8: compost, Soil amendment/ soil improver (Satriana *et al.,* 2023) R9: bio-energy (bio-oil and bio-char) (Febriyanti *et al.,* 2019; Windiastuti *et al.,* 2022; Yanti *et al.,* 2023; Fanany *et al.,* 2023)	• Economic: New business source of income for industry (ANTARA, 2022) • Environmental: Reduces waste and environmental pollution • Social: Job creation and education.
8	POME (Palm oil mill effluent)	R9: Renewable energy (Ahmad *et al.,* 2003; Ohimain and Izah, 2017; Gozan *et al.,* 2018; Antoni *et al.,* 2020; Foong *et al.,* 2020) R8: land application (Reinhart *et al.,* 2021), clean water R7: microalgae cultivation (Kumaran *et al.,* 2023)	• Economic: Reduces energy costs USD 522,108.52 during 2019 (Antoni *et al.,* 2020), save expenses cost. • Environmental: Reduces pollution and conserves resources • Social: Positive perception and awareness.

social factors, as detailed in Table 4. The contribution to the economic, environmental, and social pillars is classified into three tiers, with contributions to each sustainability pillar typically being strong or moderate, as indicated in Table 5. Conversely, there are products that contribute only marginally to benefits. A pertinent example is the conversion of leaf sheath waste into zephyr board, which yields positive environmental impacts. Palm oil shells can be used to produce liquid smoke and animal feed, which has economic benefits.

Table 5: Level of benefits of implementing a 9Rs principle on the three pillars of sustainability

No.	Type of waste	Potential products	Benefits level		
			Economic	Environment	Social
1	Tree trunk	Construction material	■	■	■
		Particle board	■	■	■
		Biopellets	■	■	■
2	Leaf sheath	Biobriquettes	■	■	■
		Zephyr board	▲	○	▲
3	Mesocarp fibres	Organic polybag	▲	▲	▲
		Biopellets	■	■	▲
		Particle board	■	■	■
		Animal feed	▲	■	▲
		Organic fertilizer/compost	■	■	■
4	Palm oil shell	Bio fuel: Biopellets and Biobriquettes	■	■	▲
		Liquid smoke	○	▲	▲
		Animal feed	○	■	■
		Organic fertilizer	■	■	▲
5	EFB	Particle board	■	■	○
		Pulp and paper	■	▲	○
		Plantation media	▲	▲	▲
		Organic fertilizer/compost	■	■	■
		Bio-char and Bio-oil	■	■	▲
		Soil amendment	■	■	○
6	POME	Renewable energy (biogas and electrical energy)	■	■	■
		Land application	○	▲	○
		Microalgae cultivation media	■	■	▲
		Liquid organic fertilizer	▲	■	▲
		Palm acid oil (PAO) for producing biodiesel or SAF	■	■	○

Remark: ■: Strong, ▲: Moderate, ○: Weak

The utilization of EFB in the manufacturing of particle board, pulp and paper, and as a soil amendment offers significant social advantages. POME used for land applications has weak economic and social benefit values. POME used as PAO for producing biodiesel or SAF is considered as potensial in terms of social benefits.

The 9Rs principle concept can reduce the rate of environmental degradation towards a sustainable palm oil industry by reducing the environmental impact by reducing the use of non-renewable and non-toxic materials and improving the environment by increasing the positive impact. Environmental effects are evident in the use of biochar products aimed at soil enhancement and the adoption of organic fertilizers in place of synthetic fertilizers. The palm oil industry can easily implement some circularity strategies, such as energy and fertilizer recovery, which can reduce energy use and synthetic fertilizers while reducing emissions. This may foster the development of regenerative innovations within the palm oil sector. The palm oil industry's challenges in transitioning traditional waste management practices to a circular economy principle system are understanding the benefits of the 9Rs principle, technological readiness to close the loop, aspects of investment readiness (related to the application of new and advanced technology), and financial incentives and institutional support for initial investment in implementation 9Rs. It is essential for government policies to be concretely

established in order to facilitate the implementation of the 9Rs. This can be achieved by offering financial incentives and institutional backing for the initial investments required. These prospective findings are recommended to be introduced to palm oil industry players as a consideration for decision making in implementing 9Rs in the palm oil industry.

CONCLUSION

Alongside its principal offerings of CPO and PKO, the palm oil industry is responsible for the production of significant quantities of by-products or waste, including solid, liquid, and gas waste. Solid waste is in the form of tree trunks, leaf stalks, leaves, fiber, solids, shells, cake, and empty oil palm bunches. The liquid waste is mainly POME, which amounts to 0.60 tons/ton of FFB. The byproducts of gas waste manifest as greenhouse gases and emissions that produce unpleasant odors. These wastes can be managed effectively by applying 9Rs principles and strategies to i) Minimize the use of primary resources through R0, R1 and R2, ii) Maximize the added value/benefits of material through R3, R4, R5, R6, R7, and minimize waste disposal through R8 and R9. The circularity strategies designated as R0, R1, and R2 are suitable for application in upstream processes, such as those occurring in oil palm nurseries and their upkeep. In contrast, strategies R7, R8, and R9 focus on the management of by-products and waste, aiming to augment their value. This study is the 9Rs principle approach for the industry that has been identified and the analysis. The identification and assessment results show that applying the 9Rs principle can increase the added value of solid and liquid palm oil waste and can be applied to palm oil mills X, Y, and Z or other palm oil mills. From the perspectives of economics, the environment, and social impact, various strategies for the effective use of palm oil waste can be identified. These include the repurposing of oil palm tree trunks, leaf stalks, and empty fruit bunches (EFB) for applications such as construction materials, particle board production, pulp and paper manufacturing, energy generation, and bio-char production. Additionally, mesocarp fibers can be utilized to create bio-pellets and bio-briquettes. Sludge can serve as an organic fertilizer or compost, while cake and solid residues can be processed into animal feed. Furthermore, palm oil shells can be employed as a fuel source for energy or steam generation within factories, and palm oil mill effluent (POME) can be harnessed as a raw material for electrical energy through methane capture, with the treated effluent providing a medium for microalgae cultivation. The residual oil content in POME remains notably high. This oil can be recovered using either mechanical or manual techniques and serves as a valuable raw material for the synthesis of biodiesel or sustainable aviation fuel. Applying the 9Rs principle based on palm oil waste can provide significant economic, environmental, and social benefits, thereby increasing the sustainability of the palm oil industry and encouraging the creation of regenerative innovation in the palm oil industry. Given that the local conditions of palm oil plantations and mills play a crucial role in determining the feasibility of circular strategy options, it is imperative to undertake a techno-economic assessment. This assessment will aid in formulating a strategy that aligns with the actual local conditions, thereby allowing for a detailed evaluation of the cost implications and the potential financial, environmental, and social benefits that could be realized in that specific context. Some technologies are identified to have great potential to close the material and energy loop within the framework of 9Rs principle. This methodology employs electrocoagulation technology for the enhanced processing of POMSE, coupled with adsorption methods to recycle liquid waste into a source of potable water. Furthermore, it involves the pyrolysis of empty fruit bunches (EFB) to yield biochar for soil improvement, and the extraction of oil residues that can be transformed into biodiesel or sustainable aviation fuel.

AUTHOR CONTRIBUTIONS

S. Suprihatin, the corresponding author, coordinated and compiled research ideas, interpreted data and research results and enriched the discussion with supporting analysis. N.S. Indrasti contributed to analyzing solid waste data and interpreting the findings. H. Prasetya analyzed and interpreted the results from economic and sustainability aspects. L. Agustina analyzed liquid waste data and interpreted laboratory data. E. Yulistika assisted with data collection and processing, connecting findings with existing literature, and drafting the manuscript.

ACKNOWLEDGEMENT

The authors would like to thank the Indonesian Palm Oil Research Fund Management Agency (BPDPKS) for the 2023 Palm Oil Research Grant

Scheme (GRS) number [PRJ-87/DPKS/2023], which provided financial support for this research, and PTPN IV for allowing us to conduct research in Palm Oil Mills under its management.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to the publication of this manuscript. Furthermore, the author has fully adhered to ethical standards, including addressing issues such as plagiarism, informed consent, misconduct, data fabrication and falsification, duplicate publication and submission, and redundancy.

OPEN ACCESS

©2024 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. Suppose the material is not included in the article's Creative Commons license, and your intended use is prohibited by statutory regulation or exceeds the permitted use. In that case, you must 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 about jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

9Rs	Nine circular strategy
%	Percent
^0C	Derajat celcius
BOD	Biological oxygen demand
CH_4	Methane gas
CO	Carbon monoxide
COD	Chemical oxygen demand
CO_2	Carbon dioxide
CPO	Crude palm oil
EFB	Empty palm oil bunches
FFB	Fresh fruit bunches
Ha	Hectare
H_2	Hydrogen
h	Hour
Kg	Kilogram
m^3	Cubic meter
OPSh	Oil palm shell
PAO	Palm acid oil
PKO	Palm kernel oil
PP	Payback period
POC	Palm oil clinker
POFA	Palm oil fuel ash
POM	Palm oil mill
POME	Palm oil mill effluent
POMs	Palm oil sludge
POMSE	Palm oil mill secondary effluent
R0	Refuse
R1	Rethink
R2	Reduce
R3	Reuse
R4	Repair
R5	Refurbish
R6	Remanufacture
R7	Repurpose
R8	Recycle
R9	Recover
SAF	Sustainable aviation fuel
TSS	Total suspended solids
WWTP	Wastewater treatment plan

REFERENCES

Abdullah, D.; Kurniawan, E.; Ginting, Z.; Ishak, I.; Dewi, R., (2022). Pemanfaatan limbah serabut kelapa sawit (elaeis guineensis jacg.) sebagai sumber energi alternatif dalam pembuatan biopelet. Chem. Eng. J. Storage. 2(2): 11-24 (**14 Pages**).

Abioye, K.J.; Harun, N.Y.; Arshad, U.; Sufian, S.; Yusuf, M.; Jagaba, A.H.; Ighalo, J.O.; Al-Kahtani, A.A.; Kamyab, H.; Kumar, A.; Prakash, C.; Okolie, J.A.; Ibrahin, H., (2024). Response surface methodology and artificial neural network modelling of palm oil decanter cake and alum sludge co-gasification for syngas (CO+H2) production. Int. J. Hydrogen Energy. 84(2024): 200-214 (**15 Pages**).

Abioye, K.J.; Harun, N.Y.; Sufian, S.; Yusuf, M.; Jagaba, A.H.; Waqas, S.; Ayodele, B.V.; Kamyab, H.; Alam, M.; Gupta, M.; Gill, H.S.;

Rezania, H.; Chelliapan, S.; Kang, K., (2024b). Optimization of syngas production from co-gasification of palm oil decanter cake and alum sludge: An RSM approach with char characterization. Environ. Res., 246(2024)118027: 1-16 (**16 Pages**).

Abutaha, F.; Razak, H.A.; Kanadasan, J., (2016) Effect of palm oil clinker (POC) aggregates on fresh and hardened properties of concrete construction and building materials. Constr. Build. Mater., 112(2016): 416-423 (**7 pages**).

Agustina, L.; Romli, M.; Suryadarma, P.; Suprihatin, S., (2024). Green synthesis of titanium dioxide photocatalyst using Lactobacillus bulgaricus for processing palm oil mill effluent. Global J. Environ. Sci. Manage., 10(1): 13-26 (**14 Pages**).

Ahmad, A.L.; Sithamparam, K.; Zulkali, M.M.D.; Ismail, S., (2003). Extraction of residue oil from palm oil mill effluent (pome) using organic solvent. ASEAN J. Sci. Technol. Dev., 20(3 and 4): 385-394 (**10 Pages**).

Alam, A.S.A.F.; Er, A.C.; Begum, H., (2015). Malaysian oil palm industry: prospect problem. J. Food Agric. Environ., 13(2): 143–148 (**6 Pages**).

ANTARA, (2022). Kemenperin kembangkan mesin olah limbah sawit jadi bahan baku kertas. Kantor Berita Indonesia.

Antoni; Siregar, Y.I.; Suwondo., (2020). Strategi pemanfaatan palm oil mill effluent (POME) sebagai sumber energi berkelanjutan di pabrik kelapa sawit PT. meridan sejati surya plantation kabupaten siak. ZONA J. Lingkungan**,** 4(2): 50-59 (**10 Pages**).

Asadpour, r.; Yavari, S.; Kamyab, H.; Ashokkumar, V.; Chelliapan, S.; Yuzir, A., (2021). Study of oil sorption behaviour of esterified oil palm empty fruit bunch (OPEFB) fibre and its kinetics and isotherm studies. Environ. Technol. Innovation. 22(2021)101397: 1-12 (**12 Pages**).

Ayres, R.U.; Ayres, L.W., (2002). A handbook of industrial ecology. Eds. Edward Elgar, Cheltenham, UK. Northampton MA, USA.

Baihaqi, R.A.; Pratama, W.D., (2023). Feasibility study of utilization of palm oil mill effluent (POME) as a source for microalgae nutrients. J. Emerg. Sci. Eng., 1(1): 1-5 (**5 Pages**).

Bantacut, T.; Novitasari, D., (2016). Energy and water self-sufficiency assessment of the white sugar production process in Indonesia using a complex mass balance model. J. Cleaner Prod., 126 (2016): 478-492 (**14 Pages**).

Bappenas**, (**2022**)**. The future is circular: langkah nyata inisiatif ekonomi sirkular di indonesia. Cleanomic: Jakarta. **(170 Pages).**

Baskaran, M.; Hashim, R.; Said, N.; Raffi, S.M.; Balakrishnan, K.; Sudesh, K.; Sulaiman, O.; Arai, T.; Kosugi, A.; Mori, Y.; Sugimoto, T.; Sato, M., (2012). Properties of binderless particleboard from oil palm trunk with addition of polyhydroxyalkanoates. Composites. Part B., 43(3): 1109-1116 (**8 Pages**).

Baskaran M.; Hashim, R.; Sulaiman, O.; Awalludin, M.F.; Sudesh, K.; Arai, T.; Kosugi, A., (2017). Properties of particleboard manufactured from oil palm trunk waste using polylactic acid as a natural binder. Waste Biomass Valor., 10(1): 1-8 (**8 Pages**).

Basu, A.J.; Dirk, J.A.; van Zyl., (2006). Industrial ecology framework for achieving cleaner production in the mining and minerals industry. J. Cleaner Prod., 14(2006): 299-304 (**6 Pages**).

Bello, M.M.; Raman, A.A.A., (2017). Trend and current practices of palm oil mill effluent polishing: Application of advanced oxidation processes and their future perspectives. J Environ Manage., 198: 170–182(**13 Pages**).

BPS, (2023). Statistik kelapa sawit indonesia 2022. Badan Pusat Statistik 16(2023): Jakarta. (**152 Pages**).

Bueren. B.J.A.V; Argus, K.; Iyer-Raniga,U.; Leenders, M.A.A.M., (2023). The circular economy operating and stakeholder model "eco-5HM" to avoid circular fallacies that prevent sustainability. J. Cleaner Prod., 39 (2023) 136096: 1-9 (**9 Pages**).

Chang, S.H., (2014). An overview of empty fruit bunch from oil palm as feedstock for bio-oil production. Biomass Bioenergy., 62: 174 – 181 (**8 Pages**).

Cheah, W.Y.; Dina, S.R.P.; Leng, S.T.K.; Er, A.C., Show, P.L., (2023). Circular bioeconomy in palm oil industry: Current practices and future perspectives. Environ. Technol. Innov., 30 (2): 103050 (**13 Pages**).

Choong, Y.Y.; Chou, K.W.; Norli, I., (2017). Strategies for improving biogas production of palm oil mill effluent (POME) anaerobic digestion: A Critical Review. Renewable Sustainable Energy Rev., 82(3): 2993-3006 (**14 Pages**).

Dewi, E.; Chodijah, S.; Elina, M., (2019). The characteristics of particle board from empty fruit palm oil (elaeis guineensis jacq) using an adhesive of liquid Guava Rod Bark. IOP Conference Series: J. Phys., 1167: 1-9 (**9 Pages**).

Fanany, M.R.; Marno, S.; Prakoso, T.; Aqsa; Istyami, A.N.; Pratiwi, M.; Indarto, A., (2023). Pemodelan proses dan evaluasi ekonomi produksi bio-oil dari limbah tandan kosong kelapa sawit. J. Teknik-Media Pengembangan Ilmu dan Aplikasi Teknik., 22(2): 142-152 (**11 Pages**).

Febriyanti, F.; Fadila, N., Sanjaya, A.S.; Bindar, Y.; Irawan, A., (2019). Utilization of empty fruit bunches waste into bio-char, bio-oil, and gases with pyrolysis method. J. Chem., 3(2): 12-17 (**6 Pages**).

Foong, S.Z.Y.; Chong, M.F.; Ng, D.K.S., (2020). Strategies to promote biogas generation and utilisation from palm oil mill effluent. Process Integr. Optim. Sustainanable. 5(2021): 175–191 (**17 Pages**).

Ginayati, L.; Faisal, M.; Suhendrayatna., (2015). Pemanfaatan asap cair dari pirolisis cangkang kelapa sawit sebagai pengawet alami tahu. J. Teknik Kimia USU., 4(3): 7-11 (**5 Pages**).

Gozan, M.; Budiarto, R.; Aulawy, N.; Rahman, S.F., 2018. Techno-economic analysis of biogas power plant from pome. Int. J. Appl. Eng. Res., 13(8): 6151 -6157 (**7 Pages**).

Harahap,Y.A.; Hasibuan, K.; Dalimunthe, W.S.; Hasibuan, A., (2023). Utilization of empty oil palm bunch as an alternative of organic fertilizer at PTPN III labuhanbatu selatan. Formosa J. Sci. Technol., 2(7): 1667-1676 (**10 Pages**).

Ho, S.; Khan, M.M.H., (2020). Short review on the use of oil palm shell in concrete and activated carbon. World J. Nano Sci. Eng., 10(1): 1-13 (**13 Pages**).

Hwang, J.Z.H.; Andiappan, V.; Ng, D.K.S., (2022). Promoting circular economy between palm oil sector with multiple industries. IOP Conference Series: Mater. Sci. Eng., 1257(1): 012005 (**6 Pages**).

Irvan., (2018). Processing of palm oil mill wastes based on zero waste technology. IOP Conference Series: Mater. Sci. Eng., 309(012136): 1-8 (**8 Pages**).

Jaya, J.D.; Darmawan, M.I.; Ilmannafian, A.G.; Safitri, R., (2020). Analisis kelayakan usaha green polybag dari limbah industri kelapa sawit. J. Pemikiran Masyarakat Ilmiah Berwawasan Agribisnis. 6(1): 1-10 (**10 Pages**).

Kaniapan, S.; Hassan, S.; Ya, H.; Nesan, K.P.; Azeem, M., (2021). The Utilisation of Palm Oil and Oil Palm Residues and the Related Challenges as a Sustainable Alternative in Biofuel, Bioenergy, and Transportation Sector: A Review. Sustainability. 13(6)3110:

1-25 (**25 Pages**).

Karvinaldi, A.; Dharmawati, N.D.; Renjani, R.A., (2022). Pemanfaatan limbah tandan kosong kelapa sawit dan serabut (fiber) dalam pembuatan polybag organik. Teknotan., 16(1): 37-41 (**6 Pages**).

Khanra, A.; Vasistha, S.; Rai, M.P.; Cheah, W.Y.; Khoo, K.S.; Chew, K.W.; Chuah, L.F.; Show, P.L., (2022). Green bioprocessing and applications of microalgae-derived biopolymers as a renewable feedstock: Circular bioeconomy approach. Environ. Technol. Innovation., 28(2022)102872: 1-20 (**20 Pages).**

Kirchherr, J.; Reike, D.; Hekkert, M., (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl., 127: 221–232 (**12 Pages**).

Kumaran, M.; Palanisamy, K.M.; Bhuyar, P.; Maniam, G.P.; Rahim, M.H.A.; Govindan, N., (2023). Agriculture of microalgae Chlorella vulgaris for polyunsaturated fatty acids (PUFAs) production employing palm oil mill effluents (POME) for future food, wastewater, and energy nexus. Energy Nexus. 9(100169): 1-7 (**7 Pages**).

Lew, J.H.; May, A.K.A.; Shamsuddin, M.R.; Aqsa; Lazim, A.M.; Narasimba, M.M., (2020). Vermicomposting of palm oil empty fruit bunch (EFB) based fertilizer with various organics additives. IOP Conference Serries: Mater. Sci. Eng., 736 (2020) 052014: 1-11 (**11 Pages**).

Liew, W.L.; Kassim, M.A.; Muda, K.; Loh, S.K., (2016). Feasibility study on palm oil processing wastes towards achieving zero discharge. ARPN J. Eng. Appl. Sci., 11(4): 2400-2405 (**6 Pages**).

Mawardi, I.; Razali, M.; Zuhaimi, Z.; Ibrahim, A.; Akadir, Z.; Razak, H.; Nurlaili, N.; Ginting, A.; Ismy, A.S.; Syarif, J., (2023). Characteristics of hybrid biopellet based on oil palm wood and natural activated charcoal as a renewable alternative energy source. J. Ecol. Eng., 24(9): 80-91 (**12 Pages**).

Norrrahim, M.N.F.; Farid, M.A.A.; Lawal, A.A.; Yasim-Anuar, T.A.T.; Samsudin, M.H.; Zulkifli, A.A., (2022). Emerging technologies for value-added use of oil palm biomass. Environ. Sci.: Adv., 1: 259-275 (**17 Pages**).

Ng, K.H.; Lee, C.H.; Khan, M.R.; Cheng, C.K., (2016). Photocatalytic degradation of recalcitrant POME waste by using silver doped titania: Photokinetics and scavenging studies. Chem. Eng. J., 286: 282–290 (**9 Pages**).

Ohimain, E.I.; Izah, S.C., (2017). A review of biogas production from palm oil mill effluents using different configurations of bioreactors. Renewable Sustainable Energy Rev., 70(5): 242 – 253 (**28 Pages).**

Pambudi, G.A.; Supriyanta; Rachmadi, R.A.D., (2022). Penggunaan papan zephyr limbah sawit sebagai solusi deteriorasi bangunan terapung. Seminar Karya and Pameran Arsitektur Indonesia 2022 Design Computation for Sustainable Architecture and Urbanism. 465-477 (13 **Pages**).

Parthasarathy, P.; Aherbawi, M.; Shahbaz, M.; Mackey, H.R.; Mckay, G.; Al-Ansari, T., (2024). Conversion of oil palm waste into value-added products through pyrolysis: a sensitivity and techno-economic investigation. Biomass Convers. Biorefin., 14: 9667–9687 (**21 Pages**).

Poopalam, K.D.; Ismail, T.N.M.T.; Hanzah, N.A; Alias, A.H.; Wahab, N.A.; Ibrahin, Z.; Subramaniam, V.; Armylisas, A.H.N.; Idris, A., (2024). Utilization of oil palm biomass and Polyurethanes as sustainable construction materials: A review. Dev. Built Environ., 17: 1-20 (**20 Pages**).

Potting, J.; Hekkert, M.; Worrell, E.; Hanemaaijer, A,. (2017). Circular economy: measuring innovation in the product chain. PBL Netherlands Environmental Assessment Agency. The Hague. (**46 Pages**).

Pujono, H.R.; Kukuh, S.; Evizal, R.; Afandi; Rahmat, A., (2021). The effect of POME application on production and yield components of oil palm in Lampung, Indonesia. IOP Conference Series: Earth Environ. Sci., 648 (012058): 1-7 (**7 Pages**).

Putra, S.I.; Tawfiequrrahman, A.; Astuti, P., (2019). Kajian tekno ekonomi produksi briket limbah kelapa sawit (elaeis guineensis jacq) sebagai energi terbarukan. Thesis. Universitas Gadjah Mada.

Raharjo, B., (2020). Pemanfaatan limbah tandan kosong kelapa sawit sebagai bahan pengganti alternatif papan partikel. Indones. J. Lab., 2(2): 1-9 (**9 Pages**).

Ramon, E.;Efendi, Z.; Kusnadi, H.; Yuliasari, S.; Ishak, A.; Wulandari, W., (2022). Utilization of oil palm waste as animal feed for Bali cattle in Margomulyo Village, Central Bengkulu. International Conference on Environmental, Energy and Earth Science., 1041: 1-6 (**6 Pages**).

Reinhart,H.; Syahri, S.; Hashifah, D.G.; Hardini, L.E., (2021). Study of palm oil mill effluent for land application suitability in Lamandau regency, Kalimantan Tengah Province. Adv. Biol. Sci. Res., 19: 86-92 (**7 Pages**).

Sailah, I.; Reyhanto, F.; Puspaningrum, T.; Romli,M.; Suprihati, S.; Indrasti, N.S., (2021). Improving the quality of anaerobically-pretreated palm oil mill effluent using electrocoagulation. J. Ecol. Eng., 22(1): 112–124 (**13 Pages**).

Sajjad, A-A.; Teow, Y.H.; Wahab, A.; Hussain, M., (2018). Sustainable approach of recycling palm oil mill effluent (POME) using integrated biofilm/membrane filtration system for internal plant usage. J. Technol., 80(4): 165–172 (**8 Pages**).

Satriana; Simatupang,M.I.; Nilda, C., (2023). Potensi pemanfaatan limbah tandan kosong kelapa sawit sebagai biochar untuk peningkatan kualitas tanah. Seminar Nasional Penelitian dan Pengabdian Teknologi Hasil Pertanian., 3: 192-196 (**5 Pages).**

Satya, A.D.M.; Cheah, W.Y.; Yazdi, S.K.; Cheng, Y.; Khoo, K.S.; Vo, D.N.; Bui, X.D.; Vithanage, M.; Show, P.L., (2023). Progress on microalgae cultivation in wastewater for bioremediation and circular bioeconomy. Environ. Res., 218: 1-15 (**15 Pages**).

Setiawan, Y., (2016). Karakteristik campuran cangkang dan serabut buah kelapa sawit terhadap nilai kalor di Propinsi Bangka Belitung. Turbo. J. Program Studi Teknik Mesin., 1(1): 38–43(**6 Pages)**.

Sihvonen, S.; Ritola, T., (2015). Conceptualizing ReX for aggregating end-of-life strategies in product development. Procedia CIRP., 29: 639–644 (**6 Pages**).

Sukaryana, Y.; Zairiful; Priabudiman, Y.; Panjaitan, I., (2019). Implementation of palm kernel cake complete feed wafers based on weaning Ongole crossbreed. IOP Conference Series: Earth Environ. Sci., 260 (2019) 012052: 1-4 (**4 Pages**).

Sukiran, M.A.; Kheang L.S.; Bakar, N.A.; May, C.Y., (2011). Production and characterization of Bio-char from the pyrolysis of empty fruit bunches. Am. J. Appl. Sci., 8(10): 984 – 988 (**5 Pages**).

Sulaiman, M.A.; Ali, M.I.; Al-Amri, M.Y.; Muthusamy, K.; Budiea, A.M.A.; Nordin, N.; Duraisamy, Y.; Othman, R., (2020). Properties of concrete containing crushed palm oil clinker as partial fine aggregate replacement. IOP Conference Series: Mater. Sci. Eng., 712(012020): 1-7 (**7 Pages**).

Sulistiawati, R.; Kusrini, N.; Imelda., (2017). Analisis finansial usaha pemanfaatan limbah tandan kosong kelapa sawit. Seminar Nasional Penerapan Ilmu Pengetahuan dan Teknologi Universitas Tanjungpura., 1-7 (**7 Pages**).

Tang, Y.M.; Tan, K.T.; Wong, L.P., (2023). Palm oil mill effluent (pome) as a source of biofuels and value-added products via oil recovery: a review. J. Oil Palm Res., 1-13 (**13 Pages**).

Wardanu, A.P.; Indrasti, N.S.; Suprihatin., (2024). Green synthesis of silica nanoparticles (Si-NPs) from palm oil fuel ash (POFA) and its application to purification water: A Review. IOP Conference Series: Earth Environ. Sci., 1358: 1-12 (**12 Pages**).

Windiastuti, E.; Suprihatin, S.; Bindar, Y.; Hasanudin, U., (2022). Identification of potential application of oil palm empty fruit bunches (EFB): A review. IOP Conference Series: Earth Environ. Sci., 1063(1): 1-11 (**11 Pages**).

Yanti, R.N., (2023). Pemanfaatan limbah perkebunan kelapa sawit sebagai sumber energi terbarukan. Dinamika Lingkungan Indonesia., 10(1): 7-11 (**5 Pages**).

Yoo, H.M.; Park, S.W.; Seo, Y.C.; Kim, K.H., (2019). Applicability assessment of empty fruit bunches from palm oil mills for use as bio-solid refuse fuels. J. Environ. Manage., 234 (2018): 1–7 (**7 Pages**).

Zamri, M.F.M.A.; Milano, J.; Shamsuddin, A.H.; Roslan, M.E.M.; Salleh, S.F.; Rahman, A.A.; Bahru, R.; Fattah, I.M.R.; Mahlia, T.M.I., (2022). An overview of palm oil biomass for power generation sector decarbonization in Malaysia: Progress, challenges, and prospects. Energy Environ., 11(4): 1-24 (**24 Pages**).

AUTHOR (S) BIOSKETCHES

Suprihatin, S., Ph.D., Professor, Departement of Agroindustrial Technology, Faculty of Agricultural Engineering and Technology. IPB University, PO Box 220, Bogor, West Java, Indonesia.
- Email: *suprihatin@apps.ipb.ac.id*
- ORCID: 0000-0001-9641-8820
- Web of Science ResearcherID: GNH-5658-2022
- Scopus Author ID: 56085767200
- Homepage: https://tin.ipb.ac.id/

Indrasti, N.S., Ph.D., Professor, Departement of Agroindustrial Technology, Faculty of Agricultural Engineering and Technology. IPB University, PO Box 220, Bogor, West Java, Indonesia.
- Email: *nastitis@apps.ipb.ac.id*
- ORCID: 0000-0002-2898-4035
- Web of Science ResearcherID: ACO-9379-2022
- Scopus Author ID: 22234206800
- Homepage: https://tin.ipb.ac.id/

Prasetya, H., Ph.D., Directorate of Economic Policy, Employment and Regional Development, Research and Innovation Agency (BRIN), BJ Habibie Building 6th Floor, Jl. MH Thamrin 8 Central Jakarta 10340, Indonesia.
- Email: *hermawanprasetya@brin.go.id*
- ORCID: 0000-0002-9424-6479
- Web of Science ResearcherID: HKV-4194-2023
- Scopus Author ID: 56826129800
- Homepage: https://brin.go.id/

Agustina, L., Ph.D., Agroindustrial Technology Study Program, Faculty of Agriculture, University of Lambung Mangkurat, Jln. Jend. A. Yani Km 36, Kotak Pos 1028 Banjarbaru 70714, Indonesia.
- Email: *lya.agustina@ulm.ac.id*
- ORCID: 0000-0001-6780-0158
- Web of Science ResearcherID: GOG-9829-2022
- Scopus Author ID: 57210411885
- Homepage: https://tip.ulm.ac.id/id/dosen/

Yulistika, E., M.Eng, Agroindustrial Technology Study Program, University of Insan Cita Indonesia (UICI), Graha Binakarsa, 10th Floor, Jl. H. R. Rasuna Said No.Kav. C-18, South Jakarta, Indonesia.
- Email: *efriyulistika0798@gmail.com*
- ORCID: 0009-0008-8111-630X
- Web of Science ResearcherID: KZU-0667-2024
- Scopus Author ID: NA
- Homepage: https://uici.ac.id/

HOW TO CITE THIS ARTICLE

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.

DOI: 10.22034/gjesm.2024.10.SI.06

URL: https://www.gjesm.net/article_715645.html

Global J. Environ. Sci. Manage. 10(SI): 105-122, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH ARTICLE

Municipal panel data analysis for solid waste, local governments and citizen participation

P. Hernández Medina*, D. Pinilla Rodríguez

Department of Economics, Universidad Nacional de Chimborazo, Riobamba, Chimborazo, Ecuador

ARTICLE INFO

Article History:
Received 07 June 2024
Revised 10 August 2024
Accepted 13 September 2024

Keywords:
Citizen participation
Local government
Municipal management
Operational capacity
Solid waste

ABSTRACT

BACKGROUND AND OBJECTIVES: Solid waste management in Ecuador is the responsibility of the municipal autonomous decentralised governments and is structured in a value chain from waste collection to final disposal. This study aims to assess the impact of municipal governance, public engagement, and the presence of regulations on the quantity of solid waste collected and the probability of service delivery within the value chain. The existing body of research concerning solid waste management at the municipal level in Ecuador is relatively sparse, particularly in terms of longitudinal studies. This gap highlights the need for further investigation, as the current limitations in data hinder a comprehensive understanding of the subject.

METHODS: The estimation of the relationships was developed through panel data models, focusing on both the volume of collections and probability of providing recovery, storage, transfer and disposal services. The explanatory variables are quality of the territorial development and land use plan goals, targets and indicators. Furthermore, these factors involve the execution of the investment plan budget financial sustainability, efficiency of expenditure, fiscal dependence, participation system, participation mechanisms, participatory budget, control mechanisms, public accountability, ordinance, municipal agency and gross value added. The current study investigates solid waste collection and the delivery of services in the value chain as the dependent variables, analyzing data from 221 municipalities in Ecuador during the timeframe of 2017 to 2022.

FINDINGS: The findings indicate that in smaller municipalities, citizen participation –– either through participatory budgeting or control mechanisms – influences solid waste collection. In the realm of financial management, the significance of fiscal dependency and financial sustainability is prominent; however, the aspect of planning typically does not exhibit a considerable impact. The chances of offering services such as storage, transfers, and utilization, characterized by limited regulatory oversight, are shaped by fiscal reliance and the existence of relevant ordinances, with no observable effect from citizen participation.

CONCLUSION: The outcomes related to citizen participation and waste management are generally more favorable in smaller municipalities. This phenomenon can be linked to their enhanced social cohesion and less complex administrative systems, which promote the successful implementation of policies and initiatives that cater to the unique needs of the community. On the other hand, larger municipalities face greater challenges, such as bureaucracy and complexity in service coordination, which limits the impact of citizen participation. To increase the efficiency of solid waste management services in municipalities, irrespective of their size, it is crucial to innovate in fiscal management and to adopt clear regulatory frameworks.

DOI: 10.22034/gjesm.2024.10.SI.07

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

NUMBER OF REFERENCES
54

NUMBER OF FIGURES
2

NUMBER OF TABLES
5

*Corresponding Author:
Email: *patricia.hernandez@unach.edu.ec*
Phone: +997 909 463
ORCID: 0000-0001-8527-5158

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

In Latin America, decentralisation has emerged as a dynamic and intricate process designed to bolster efficiency, equity, and governance in the provision of public goods. This initiative entails the transfer of authority, resources, and responsibilities from the central government to sub-national governments, which include local and regional authorities. The efficient provision of public goods is one of the main objectives of decentralisation because of the leading role they play in the economic and social development of the territory and the gains in improving efficiency and accountability in the provision of these goods (Forcaut and Wan, 2017). Various theoretical perspectives, such as fiscal federalism, can elucidate the relationship between decentralization and the supply of public goods. According to this theory, delegating fiscal and administrative duties to sub-national governments may lead to improved efficiency in the delivery of these goods (Forcaut and Wan, 2017). Emphasising the management of sub-national governments, Rondinelli *et al.* (1989) propose the theory of administrative decentralisation based on the idea that decentralisation can reduce bureaucracy and streamline decision-making processes, allowing for a faster and more appropriate response to local needs. The foundation of adequate public service provision, particularly in the realm of solid waste management (SWM), lies in effective municipal management. This involves essential elements such as comprehensive planning, sound financial management, and the involvement of citizens in the decision-making process. Municipal planning – through which local authorities define objectives, strategies and actions for urban and rural development – ensures the efficient provision of public services. The significance of territorial planning in urban contexts cannot be overstated, particularly regarding the sustainability of cities through effective water and waste management (Díaz-Barriga-Fernández *et al.*, 2017). This planning approach aids in establishing efficient waste collection routes, suitable disposal sites, and comprehensive recycling strategies (Ghiani *et al.*, 2014; Carmen-Niño *et al.*, 2023). However, the effectiveness of these planning initiatives can be compromised by factors such as insufficient infrastructure, unclear regulations, disorganized public policies, and a lack of financial support (Yukalang *et al.*, 2017; Tsypkin et al., 2020; Bernache-Pérez *et al.*, 2023). Enhancing citizen involvement and integrating the informal sector into SWM could serve as potential solutions to these challenges (Ferronato *et al.*, 2019). Financial management, understood as the capacity of municipal governments to manage their economic resources efficiently and transparently through tax collection, budget management and investment in infrastructure, is essential for the acquisition of collection equipment, construction of landfills and recycling plants and implementation of environmental education programmes (Guerrero *et al.*, 2013; Lohri *et al.*, 2014; Bartolacci *et al.*, 2018; Pinha and Sagawa, 2020). In addition to analyzing territorial planning and financial management, it is crucial to take into account the relationships among individuals and communities. This comprehensive approach facilitates the integration of social capital theory (Bourdieu, 1985; Putnam, 1993), which asserts that social networks, trust, and reciprocal norms can significantly bolster the efficiency of public institutions. Putnam (1993) suggests that communities with high levels of social capital are better able to manage public goods effectively, as cooperation and civic participation facilitate the implementation of public policies and the oversight of local officials. The concept of civic participation refers to the active role of the community in the municipal decision-making process, which is achieved through public consultations, neighborhood committees, and feedback systems. Specifically regarding SWM at the local level, this participation is essential for fostering sustainable development in communities, as it significantly influences public health, environmental sustainability, and economic vitality. As cities and communities continue to grow, the amount of waste generated increases proportionally, underscoring the need for effective waste management systems (Kala and Bolia, 2021). The concept of waste management extends beyond the mere final disposal of waste; it also incorporates the stages of collection, transportation, treatment, and frequently, the recovery of materials through recycling and alternative reuse strategies. While decentralisation processes seem to contribute to waste management (Aprilia *et al.*, 2011; Masood *et al.*, 2014; Nhubu *et al.*, 2021; Angouria-Tsorochidou *et al.*, 2022; Alvarado-Ibarra *et al.*, 2024), there is also evidence that interlinkages between municipalities

can generate economies of scale in terms of reduced average costs of infrastructure, collection and processing (Villalba *et al*., 2022), incentivising environmental governance processes. A significant challenge encountered by local governments is the establishment of waste management systems that are not only efficient and sustainable but also economically feasible. According to UN-Habitat (2010), well-structured waste management at the local level should include active community participation, implementation of appropriate technologies and adaptation to the specific conditions of each localityEvidence from empirical studies indicates that active citizen engagement is essential for the successful implementation of recycling programs and waste management efforts, as it encourages responsible practices and compliance with regulatory frameworks (UN-Habitat, 2010; Guerrero *et al*., 2013; Zaman, 2023). Citizen participation allows local communities to take the lead in the creation and management of waste projects, such as recycling centres, community composting or clean-up campaigns, initiatives that not only help reduce the amount of waste going to landfills but also strengthen the social fabric. Research focused on the evaluation of experiences and key determinants for successful SWM has underscored the crucial role of environmental consciousness within the general populace (Raghu and Rodriguez, 2021). Furthermore, it has been found that citizen involvement, the actions of local government, levels of education (Ranjith and Chowdhury, 2007), infrastructural challenges, and cultural aspects are also essential components (Zhang *et al*., 2024). Studies in places such as Pakistan, India, Iran and Vietnam seem to agree that the quality of SWM is the result of the interaction between environmental governance and citizen participation (Wu *et al*., 2020) and that the higher the educational and occupational level, the less satisfied the population will be and the more they will demand and, through participation in decision-making, more efficient actions in service provision will be put in place (Ranjith and Chowdhury, 2007; Masood *et al*., 2014; Pinnawala, 2016; Jomehpour and Behzad, 2020; Raghu and Rodriguez, 2021). Active citizen participation can significantly contribute to the collaboration with local governments aimed at refining waste collection services and advancing recycling programs, ultimately fostering more robust waste management policies. Nevertheless, the role of local governments is crucial in devising community incentives, such as rewards, that motivate engagement in solid waste management initiatives. The success of these programs is heavily reliant on the willingness of households to embrace recycling practices (Kala and Bolia, 2021). In the realm of community engagement, it is important to acknowledge that the effectiveness of citizen participation in SWM is contingent upon the size of the municipality. Empirical evidence seems to show that the smaller the population, the more efficient community management is and therefore the greater impact it has on the value chain of SWM, while in larger municipalities, this management is more complex, bureaucratic and less flexible, which limits citizen participation (Guerrero *et al*., 2015; Houwelingen, 2017; Benito *et al*., 2021; McDonnell, 2019 and 2022). Furthermore, the effectiveness of SWM can be shaped by the implementation of ordinances. Such regulations play a crucial role in promoting efficiency and ensuring the protection of the environment and the well-being of the community (Batista *et al*., 2021; Kiguli *et al*., 2023). It can also be influenced by the management model, either directly by the municipality or through outsourcing. There is a notable divergence of opinion within the academic literature concerning the optimal model for waste management. Some researchers assert that municipal management is not the most suitable approach, particularly in the context of larger municipalities (Pérez-López *et al*., 2016; Campos-Alba *et al*., 2021; Doussoulin and Colther, 2022). In contrast, other studies suggest that smaller municipalities are capable of managing waste efficiently (Romano and Molinos-Senante, 2020). With regard to the economic growth of municipalities, the literature provides evidence of a relationship that depends on the stage of development of the municipality; as the territory grows, waste generation increases, and only after a certain level of growth is reached are environmental practices introduced to compensate for this increase, showing an inverse relationship from there (Magazzino *et al*., 2020). Research conducted in Peru, Brazil, Bolivia, and Mexico reveals that the effectiveness of recycling practices and municipal SWM programs in Latin America is significantly influenced by factors such as citizen engagement, municipal environmental governance, as well as the

educational attainment, age, and gender of the population (Bernal *et al*., 2020; De Oliveira et al., 2023; Alvarado-Ibarra *et al*., 2024). In the specific case of Ecuador, a decentralisation trajectory has been followed, marked by significant constitutional and legal reforms, such as the 2008 Constitution and the Organic Code of Territorial Organisation, Autonomy and Decentralisation (COOTAD in Spanish), which are the legal pillars governing the decentralisation process in the country. In Ecuador, local governments—comprising provincial, municipal, and parish entities, play a vital role in the enactment of public policies and the provision of various services to the community. Decentralised autonomous governments (DAGs) have exclusive, concurrent and complementary competencies in several key areas for local development and public wellbeing, such as land management through territorial order and development plans (TODPs) that promote sustainable land use and the balanced development of urban and rural areas. The responsibilities of DAGs include the provision of essential public services. This involves the management of drinking water resources, sewage systems, and the collection and treatment of solid waste. They are also tasked with maintaining public lighting and road infrastructure. In terms of environmental stewardship, DAGs implement policies and programs designed to protect the environment, conserve natural resources, and mitigate climate change effects. Additionally, they support productive and economic development by encouraging local economic activities. SWM in Ecuador has undergone a significant evolution in recent decades, marked by a growing effort by local and national authorities to improve waste management practices and reduce their environmental impact, regulated by a series of laws and policies that seek to establish a framework for proper waste management, such as the Environmental Management Law, passed in 1999, and the Organic Environmental Code of 2018. These legislation supports efforts to minimize waste generation, enhance material recovery, and ensure proper disposal methods, in addition to promoting the integration of waste management policies into local development frameworks (Ministerio del Ambiente, 2015). One of the main challenges in Ecuador is the limited capacity of municipalities to implement and maintain effective waste management systems. Numerous municipalities, particularly those situated in rural regions, face significant challenges due to insufficient financial and technical resources for the effective management of solid waste. The consequence of this situation has been an increased dependence on open dumping sites, which fail to comply with environmental regulations and present considerable threats to both public health and ecological integrity. Another problem is the lack of adequate infrastructure for selective collection and recycling; although pilot recycling programmes have been implemented in cities such as Quito, Guayaquil and Cuenca, they have not achieved sufficient coverage to have a significant impact on a national level (Chicaiza *et al*., 2020; Burneo *et al*., 2020). This issue is intensified by a lack of active citizen involvement in source separation programs, thereby impeding the establishment of more sustainable waste management systems. Given the local challenges of responding to sustainable development in the country and promoting nature conservation and public wellbeing, as well as the scarce empirical evidence available in the country and even more so at a municipal (cantonal) level, this study had two aims. The primary aim of this study was to assess whether advancements in the operational capacity of municipal government management and the involvement of citizens result in a greater quantity of waste collected, serving as the initial step in the value chain. The second aim was to ascertain whether these factors lead to an increase in the volume of waste collected during the initial phase of the value chain, and to evaluate if these factors influence the likelihood of subsequent processes within the value chain. This includes collection, which currently lacks explicit legal regulations and is often conducted through informal arrangements, as well as storage, transfer, utilization. In order to address the influence of citizen participation and municipal government management in the provision of local public services such as solid waste for the years 2017–2022 in the 221 Ecuadorian municipalities in Ecuador.

MATERIALS AND METHODS

Information regarding the operational capabilities of municipal Decentralized Autonomous Governments (DAGs) was obtained from the National Council of Competencies (CNC, 2023) and the Census of Environmental Economic Information on Municipal DAGs provided by the National

Table 1: Components and indicators of the operational capability index (Consejo Nacional de Competencias, 2023)

Dimension	Component	Indicator / Estimate
Planning and spatial planning	Quality of the TODP	This is constructed by identifying the errors in the formulation of objectives, goals and indicators of the TODP with respect to the total number proposed.
	Articulation of programmes and projects to the TODP	Number of projects whose linkage to the TODP goal is incorrect. Number of projects whose linkage to the competence is incorrect. Total number of programmes or projects entered.
	Goal fulfilment index (GFI)	The comparison procedure is applied with the best score in the fulfilment of goals.
Financial management	Investment budget execution Financial sustainability Efficiency in investment and capital spending Fiscal dependence	Comparison with the best score is applied. Indicators are used, whose values range from 0 percent (%) to 100% and for which it is not possible to determine a range of optimal to poor performance of the indicator.
Citizen participation	Citizen participation system implemented	This includes: a call for participation, ordinance of approval, citizen participation system implementation and local planning council.
	Citizen participation mechanisms implemented	This includes: local citizens' assembly, public hearings, people's council, the empty chair (consists of the allocation of a space or chair within the sessions of the GADs, destined to a representative of the citizens. Although the empty chair representative does not have the right to vote, his or her participation allows the voice of the citizenry to be heard in the decision-making process) and consultation councils
	Participatory budget	This includes: participatory budgeting and percentage of budget allocated for participatory budgeting.
	Mechanism of social control by the citizenry	This includes: citizen oversight agencies, citizen observatories, community ombudsmen for the management of the DAG and user committees for the management of services.
	Implementation of the full accountability process	This includes: a delivered accountability report to the Citizen participation council (CPC), receipt of issues that citizens need to be informed of, the participation body / DAG creating a joint team for the accountability process, public deliberation and citizen evaluation of the accountability report carried out in person, a work plan to incorporate citizen suggestions, the DAG delivering the work plan to the citizen assembly, planning council and participation bodies for monitoring.

Institute of Statistics and Censuses (INEC, 2023). The assessment of the operational capacity of the 221 municipal governments pertains to the extent to which the decentralized autonomous government can effectively exercise its competencies, functions, and responsibilities (CNC, 2023). To this end, the National Council of Competencies of Ecuador (Consejo Nacional de Competencias, 2024) estimates an operational capacity index (OCI) made up of three dimensions: territorial planning and organisation, financial management and citizen participation, which group together components and indicators (Table 1). The maximum score of the OCI is 30 points, with each dimension contributing a maximum of 10 points.

Concerning the dependent variable, the research focused on the volume of solid waste collected (in tonnes per month) and the provision of essential value chain processes—namely collection, storage, transfer, utilization, and final disposal, across all municipalities throughout the designated study period (INEC, 2023). Information on these variables is available longitudinally (2017 to 2022) and for all 221 municipalities, which requires the estimation of a panel data model. These variables have been considered based on what is proposed in the literature and the existing limitations of municipal-level data in Ecuador. Although the provincial and national levels offer opportunities to include other critical variables associated with demographic and economic considerations, there is a significant absence of trustworthy and systematic information at the municipal level. Despite global advances in technology, digital citizen participation (e-participation) has not been implemented in Ecuador, making it impossible to include it in the

estimation. First, the dependent variable concerning solid waste collection, quantified in tonnes per month, was examined using fixed or random effects panel data estimates. This methodology was implemented to account for the heterogeneity that stems from differences among municipalities or random variations. The existence of unobserved heterogeneity means that the regression error term contains not only the residuals of the estimation itself, which is part of the variability of the dependent variable not explained by the model, but also an error associated with unobserved heterogeneity (Wooldridge, 2010). Unobserved heterogeneity gives rise to a correlation between the error component and the explanatory variables, thereby hindering the ability to derive unbiased estimators. To overcome this bias, fixed effects estimation and random effects estimation have been proposed (Wooldridge, 2010; Montero, 2011). The first scenario suggests that unobserved heterogeneity arises from individual characteristics, which results in a correlation. In contrast, the second scenario posits that unobserved heterogeneity is a consequence of randomness, leading to the assumption that the correlation with the explanatory variables is nonexistent. The model that best explains the unobserved heterogeneity was selected by means of the Hausman test, whose hypothesis is based on the preference of the random effects model over the fixed effects model (Montero, 2011). Upon selecting the fixed effects model, it was necessary to determine the presence of heteroscedasticity (modified White test) and autocorrelation (Wooldridge test). The presence of one or both problems should be corrected using generalised least squares (GLS) for fixed effects (Wooldridge, 2010; Montero, 2011). In the first instance, the estimation of the solid waste variable y_it was conducted using a variety of components from the planning dimension (X_it), which includes the quality of the objectives, indicators, and goals associated with the TODP. The financial management component (Z_it) was also incorporated, which consists of budget execution for investments, financial sustainability, fiscal dependence, and the efficiency of capital expenditures. Additionally, the citizen participation component (W_it) was evaluated, comprising participatory budgeting, mechanisms for participation, and accountability measures. The existence of a municipal ordinance for management was treated as a dichotomous variable (V_it), assigned a value of zero if it is not present. Other relevant factors included the gross value added from the municipality's production (T_it) and whether the municipality directly manages the operations (U_it), which is also a dichotomous variable, taking a value of zero when managed by another entity, as specified in Eq. 1 (Pinha and Sagawa, 2020; Kala and Bolia, 2021):

$$y_{it} = \beta_0 + \beta_1 X_{it} + \beta_2 Z_{it} + \beta_3 W_{it} + \beta_4 V_{it} + \beta_5 U_{it} + \beta_6 T_{it} + \varepsilon_{it} \quad (1)$$

In addition, the execution of SWM value chain processes, which include collection, storage, transfer, recovery, and disposal, can be classified as dichotomous variables. This classification supports the use of discrete choice modeling through logit panel data, which is governed by a logistic distribution function. y_{it} is the dichotomous variable associated with the provision of collection, storage, transfers, use and final disposal, with a value of zero if the municipality does not provide the service, while the explanatory variables are those used in Eq. 1. Each dependent variable is estimated using a logit model in panel data, both for fixed and random effects. As indicated, the selection of the determination of the appropriate model for each effect is based on the findings of the Hausman test. Utilizing the selected model, the marginal effects are derived from partial derivatives, demonstrating the variation in the probability of service provision resulting from a one-unit alteration in each indicator.

RESULTS AND DISCUSSION

When analysing the behaviour of the provision of public services in the study period for all 221 municipalities, it is evident that only 53.46% of the municipalities carried out the process of SWM. These findings stem from Ecuador's commitment to the National Programme for the Integrated Management of Solid Waste (NPIMSW), which has been in operation for over a decade. The Ministry of Environment oversees the program, with municipal governments responsible for its execution. Additionally, the Organic Environmental Code, enacted in 2018, enforces the necessity of effective waste management strategies (Consejo Nacional de Competencias, 2019). In 2022, the management model employed by municipal governments was primarily directed towards direct

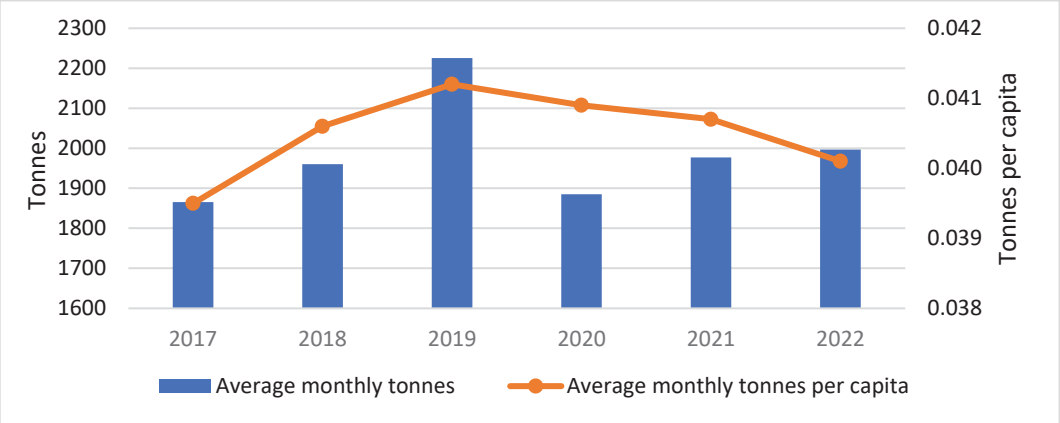


Fig. 1: Evolution of average monthly solid waste collection (2017–2022) (INEC, 2023)

or combined administration, which comprised 85% of the overall management approach. This was succeeded by joint public companies at 8.6%, municipal enterprises created by governmental bodies for service provision at 5.5%, and associations of municipalities, which involve the collaboration of multiple municipal governments for collective task execution, accounting for 0.9%. INEC (2023) outlines that the value chain associated with integrated solid waste management (SWM) is bifurcated into two distinct sources, regardless of the management model implemented. The initial source consists of fundamental services, including collection, source separation, and street cleaning, which are legally designated as the responsibility of municipal governments, typically underpinned by relevant ordinances. The second source relates to the overall value chain of integrated SWM, irrespective of the management model in place. This comprises storage, transport, transfer or collection, use and final disposal, all of which do not have defined regulations, giving rise to informality and commercial activity derived from these processes (Ministerio del Ambiente, 2015). The evolution of the results of the first source of the value chain (collection), despite the population increase, have not improved throughout the period analysed, neither in absolute terms of tonnes collected nor in per-capita terms. In terms of average monthly collection, 2019 stands out as the peak year. Conversely, 2020 experienced a reduction exceeding 300 tonnes per month, primarily due to the impacts of the sanitary emergency, restrictions on mobility, and enforced isolation measures. The situation gradually recovered without exceeding the results of 2019, reaching 40.15 kg per month per inhabitant by 2022 (Fig. 1).

The results in terms of the first source of the value chain (collection) can also be compared by cantonal population size, according to the classification proposed by the Environment Ministry (Ministerio del Ambiente), in which a canton is considered large if it has more than 300,001 inhabitants, medium between 50,0001 and 300,000, small between 15,001 and 50,000, and micro when less than 15,000 inhabitants. According to the data presented in Table 2, the monthly average of solid waste collected reached 1,996.75 tonnes by 2022. The municipalities with the largest populations reported an average collection of 48,917.58 tonnes per month, contrasting sharply with the smaller cantons, which averaged only 231.19 tonnes. This indicates that while total waste collection increases with population size, the per-capita collection remains modest, averaging 38.54 kg per month. The canton of Tiwintza had the lowest per-capita collection, whereas Las Naves recorded the highest at 112.11 kg for the year 2022.

In the context of SWM, only 53.39% of municipalities deliver a complete range of services across different management modalities. The value chain particularly underscores the importance of collection, street cleaning, and final disposal processes, which are carried out by more than 90% of municipalities on average. Nonetheless, the level of service provision tends to be lower in larger cantons. Of the total waste

Table 2: Variables associated with SWM by canton (Municipality) size for the year 2022 (INEC, 2023)

Variables	Large	Medium	Small	Micro	Total or overall average
N° municipalities	6	34	43	138	221
Solid waste (tonnes per month collected)	48,917.58	3,510.91	962.35	231.19	1,996.75
Proportion of municipalities providing SWM services	33.33%	59.80%	54.26%	67.39%	53.39%
Proportion of municipalities with collection ordinances	83.33%	97.06%	93.02%	92.02%	92.76%
Proportion of municipalities with direct management	60.00%	73.53%	95.35%	85.50%	85.00%
Proportion of municipalities with service charges	100%	97.06%	95.35%	93.47%	94.54%
Proportion of municipalities that provide training for citizens	33.33%	26.47%	46.51%	36.23%	36.65%
Proportion of municipalities that have received technical assistance	20.00%	61.76%	62.79%	55.97%	56.81%
Proportion of municipalities with waste collection processes	33.33%	11.76%	30.23%	23.18%	23.07%
Proportion of municipalities with final management processes	83.33%	94.12%	95.35%	94.92%	94.57%
Proportion of municipalities with transfer processes	16.67%	2.94%	0.00%	2.17%	2.26%
Proportion of municipalities with collection processes	83.33%	100%	100%	100%	99.54%
Proportion of municipalities with sweeping processes	50.00%	97.06%	97.67%	97.82%	96.38%
Proportion of municipalities with storage processes	16.67%	17.65%	4.65%	15.94%	14.02%

disposed of, 54.5% is managed in sanitary landfills, 28.2% in temporary cells, and 17.3% in dumps (INEC, 2023). The processes of storage, transfer and use are the ones with the lowest percentage of provision regardless of the population size of the municipality. Additionally, most municipalities have ordinances for waste collection and, in general terms, for waste management, as this is the direct competence attributed to them by the Organic Environmental Code, but not for the additional processes of the value chain, which could explain the low rate of provision of these services. These ordinances are also associated with charging for the service, but according to INEC (2023), the subsidy granted by the municipal governments was 47.3% of the amount of the service, which amounted to 27 million USD for the year 2022. The assessment of municipal governments' operational capacity as a determinant of their effectiveness in solid waste collection reveals, as illustrated in Fig. 2, that the Operational Capacity Index (OCI) has generally progressed from 2017 to 2022, although a regression is apparent in the last year. This improvement has been driven by the dimension of planning related to the TODP, which is the best evaluated, followed by citizen participation and, in last place, financial management, showing weaknesses in resource management.

The analysis for the year 2022, particularly when considering population size, demonstrates that the operational capacity indices are largely similar, although the largest municipalities exhibit slightly diminished results. The dimensions of planning, financial management, and citizen participation each possess a maximum indicator value of 10 points. Therefore, the cumulative maximum value of the index, derived from the sum of these dimensions, totals 30 points. This implies that higher results are indicative of greater operational capacity, as demonstrated in Table 3.

The higher the values of the quality of the TODP, the articulation of projects and the compliance rate, the better the quality of the planning carried

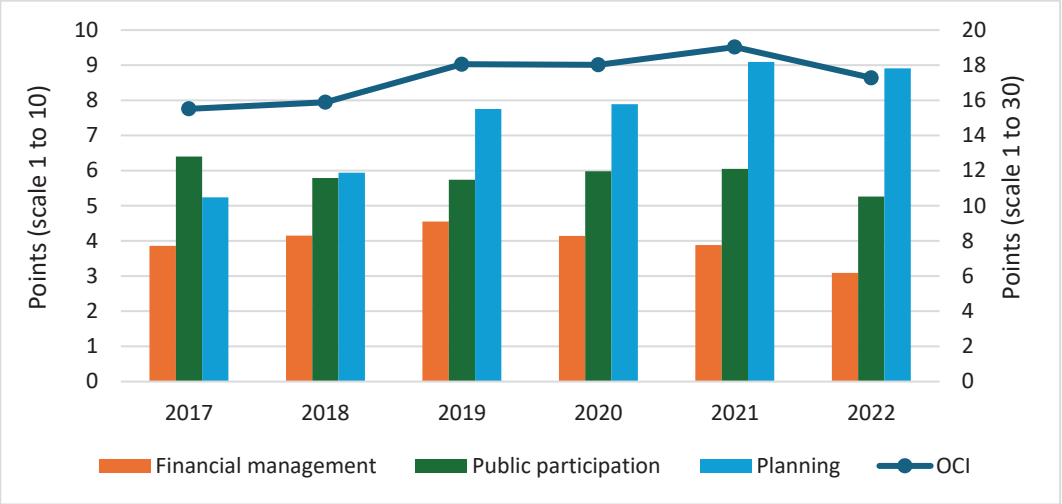


Fig. 2: Evolution of the municipal OCI (2017–2022) (CNC, 2024)

Table 3: Municipal management and citizen participation by canton size (municipality) for the year 2022 (CNC, 2023)

Dimension / Indicator	Large	Medium	Small	Micro	Overall average	Maximum value
Planning						
Quality of the TODP	1.44	1.49	1.41	1.40	1.44	1.54
Articulation of TODP projects	1.28	1.48	0.49	1.46	1.46	1.54
Compliance Index	5.67	6.24	6.23	5.95	6.03	6.92
Financial Management						
Investment budget execution	1.81	2.12	2.06	2.06	2.06	2.50
Financial sustainability	0.42	0.22	0.17	0.24	0.22	2.50
Expenditure efficiency	0.13	0.17	0.10	0.11	0.12	2.50
Fiscal dependence	0.87	0.69	0.63	0.70	0.68	2.50
Citizen Participation						
Participation system	1.71	1.59	2.14	1.80	1.83	2.86
Participation mechanisms	1.28	0.88	1.16	1.03	1.03	2.62
Participatory budget	0.16	0.37	0.35	0.36	0.35	0.95
Control mechanisms	0.09	0.04	0.04	0.05	0.04	0.71
Public accountability	1.65	1.82	2.21	1.98	1.99	2.86
OCI	16.36	17.08	17.98	17.15	17.28	30

out by the municipal governments. Likewise, a more effective implementation of the investment plan, coupled with financial sustainability, optimal resource utilization, and diminished fiscal reliance, leads to superior results in the indicators of financial management. In this scenario, budget execution emerges as the metric with the most significant values, while the performance indicators related to financial sustainability, spending efficiency, and fiscal dependence fall short of even the average benchmark the scale. In the Andean region, the municipalities that reported the best OCI performance, slightly exceeding 20 points, were: Guano and Riobamba (province of Chimborazo), Cañar (province of Cañar), San Miguel de Urcuquí (province of Imbabura) and Quito, Mejía and Rumiñahui (province of Pichincha). In the coastal region, the highest-performing municipalities were: Pasaje and Piñas (province of El Oro), Atacames (province of Esmeraldas), Guayaquil and Samborondón (province of Guayas), and Santo Domingo (province of Santo Domingo de los Tsáchilas). The municipalities with the lowest

performance, around 10 points, were San Cristóbal (Galápagos), Muisne (Esmeraldas) and Sucumbíos (province of Sucumbíos). In the Amazon region, the municipality of Sucumbíos stood out with a performance score of 10.65 points, as no other municipalities demonstrated exceptional results. Additionally, the Andean region did not present any municipalities with significantly low scores. To test the relationship between solid waste collection (tonnes/month), we made panel data, fixed effects (FE) and random effects (RE) estimates for all municipalities as well as for each population size group. The selection of the Hausman test was based on its capacity to effectively account for the heterogeneity in the data, which in turn validated the assumptions and rectified the heteroscedasticity issues identified in the fixed effects model. The results for all five models are detailed in Table 4.

The fixed effects model was chosen for the estimation of all municipalities, both medium and small. However, due to the presence of heteroscedasticity, a GLS correction was applied to the panel data. In contrast, random effects were employed for the remaining municipalities, which include large and micro entities. In all cases the gross value added of production (equivalent to the gross

Table 4: Panel data estimation for solid waste collection (tonnes/month) by municipality size

Variables	Total (FE GLS)	Large (RE)	Medium (FE GLS)	Small (FE GLS)	Micro (RE)
Quality of the TODP goals	-1177.671	-67037.15*	1364.025	-9.460976	3.7605
	(1837.07)	(35952.66)	(1895.447)	(522.956)	(18.346)
Quality of the TODP targets	1663.591	4298.397	2968.25	-562.0477	19.7618
	(1799.39)	(42591.31)	(1854.263)	(487.912)	(16-995)
Quality of the TODP	2505.634	20468.06	-208.849	123.037	-0.7735
indicators	(1797.32)	(64264.78)	(1889.315)	(479.780)	(17.182)
Budget execution of the	-153.1595	-6486.683	559.481	21.040	0.1935639
investment plan	(443.618)	(11258.18)	(407.033)	(121.771)	4.513661
Financial sustainability	4594.658***	664.7579	93.7492	808.802***	-5.7927
	(890.247)	(8972.528)	(571.702)	(252.535)	(14.153)
Efficiency of expenditure	-744.152	-3398.213	-11.4724	-548.675*	4.6511
	(1100.327)	(8107.959)	(886.412)	(310.202)	(11.180)
Fiscal dependence	2831.954*	28347.2	-1956.161**	1594.467***	29.364
	(1457.3)	(20810.4)	(821.711)	(406.329)	(19.380)
Participation system	88.3598	4035.535	140.6384	-16.017	2.8237
	(324.773)	(8508.567)	(318.683)	(106.625)	(3.7364)
Participation mechanisms	19.8009	1867.815	-1444.565***	-112.473	-0.8556
	(479.257)	(8176.541)	(423.602)	(129.812)	(5.7974)
Participatory budget	4861.322***	-30319.77	274.4882	-417.331	28.920**
	(1446.706)	(30114.83)	(1338.315)	(404.101)	(14.562)
Control mechanisms	8057.146***	-4782.181	2986.632	1526.289**	-15.6472
	(2249.045)	(17605.57)	(2232.035)	(620.901)	(26.604)
Public accountability	244.7293	-1515.257	-823.4892**	249.565*	-2.1526
	(390.647)	(11511.33)	(409.805)	(135.083)	(3.8772)
Ordinance	1119.522	23699.04	-1481.042**	833.26***	15.83896**
	(753.347)	(15695.27)	(656.402)	(219.897)	(8.0643)
Municipal agency	-766.449	19029.42	-214.311	-554.231**	77.2502***
	(733.574)	(12399.48)	(591.435)	(244.648)	(13.742)
Gross value added	0.00024**	0.0030***	0.00589***	0.0028***	0.000067
	(0.00012)	(0.00067)	(0.000063)	(0.00014)	(0.00004)
Constant	-6827.579***	-22496.69	2346.257	-1642.29***	134.788***
	(1971.578)	(60825.82)	(1922.964)	(621.434)	(36.047)
Wald chi^2	136.54***	110.72***	9965.74***	805.50***	57.11***
Hausman	66.13***	0.44	35.74***	29.51***	4.38
R^2 overall	0.0535	0.9326	0.9770	0.5903	0.0241
R^2 within	0.020	0.6250	0.5517	0.1713	0.0755
R^2 between	0.0696	0.9999	0.9802	0.6968	0.0240
Rho	0.9650	0.9386	0.8723	0.8513	0.9532

Note: Values in brackets are standard errors. Variables significant at 1% ***, 5% **, 10% *.

Table 5: Marginal effects (partial derivatives) of the estimation of the logit model in panel data for SWM processes

Variables	Collection (FE)	Storage (RE)	Transferences (RE)	Use (RE)	Final disposal (RE)
Quality of the TODP goals	0.0223	0.0301	0.0291	0.1236*	-0.0305
	(0.0494)	(0.0329)	(0.0489)	(0.0668)	(0.0573)
Quality of the TODP targets	-0.0302	-0.0136	0.0025	0.0300	0.0465
	(0.0475)	(0.0162)	(0.0498)	(0.0640)	(0.0555)
Quality of the TODP indicators	0.0856*	-0.0160	0.0967*	-0.0017	0.0702
	(0.0485)	(0.0179)	(0.0498)	(0.0641)	(0.0572)
Budget execution of investment plan	-0.0243*	-0.00003	-0.0159	-0.0180	-0.0081
	(0.0145)	(0.0026)	(0.0128)	(0.0149)	(0.0156)
Financial sustainability	0.0381	0.0215	0.0223	-0.0268	-0.0515
	(0.0373)	(0.0212)	(0.0279)	(0.0337)	(0.0361)
Efficiency of expenditure	0.0176	-0.0094	-0.3343***	-0.0234	0.2913***
	(0.0338)	(0.0118)	(0.0526)	(0.0328)	(0.0421)
Fiscal dependence	-0.0802	-0.0719	0.1690***	0.17203***	-0.1773***
	(0.0492)	(0.0596)	(0.0411)	(0.0534)	(0.0511)
Participation system	-0.0083	-0.0002	0.0049	0.0120	0.0036
	(0.0116)	(0.0024)	(0.0098)	(0.0122)	(0.0121)
Participation mechanisms	-0.0059	-0.0007	0.0156	0.0051	-0.0114
	(0.0164)	(0.0036)	(0.0144)	(0.0178)	(0.0177)
Participatory budget	-0.0184	0.0059	-0.0992***	-0.0082	0.0078
	(0.0472)	(0.0115)	(0.0480)	(0.0505)	(0.0512)
Control mechanisms	0.0822	0.0009	0.0651	0.0618	0.0763
	(0.0767)	(0.0144)	(0.0589)	(0.0817)	(0.0786)
Public accountability	-0.0085	0.0082	0.0008	-0.0254*	0.0096
	(0.0121)	(0.0090)	(0.0110)	(0.0140)	(0.0134)
Ordinance	0.5296***	-0.0320	-0.1131***	0,1411***	0.4341***
	(0.0464)	(0.0280)	(0.0249)	(0,0272)	(0.0205)
Municipal agency	0.0264	-0.0300	-0.0326	0,0013	-0.0003
	(0.0299)	(0.0275)	(0.0207)	(0,0376)	(0.0314)
Wald chi^2/LR	89.88***	139.35***	95.50***	47.83***	192.65***
Hausman	28.32**	8.16	11.24	8.20	228.19***

Note: Values in brackets are standard errors. Variables significant at 1% ***, 5% **, 10% *.

domestic product per municipality) was significant, having a positive effect on solid waste collection. At the aggregate level, the results indicate that some indicators of financial management are significant, but not those related to territorial planning. A clear and substantial correlation was found between the collection of solid waste and both financial sustainability and fiscal dependency. Furthermore, regarding citizen engagement, the presence of participatory budgets, an increased allocation of budgetary resources to these initiatives, and a higher number of oversight mechanisms contribute positively to the efficiency of solid waste collection. Neither the existence of by-laws nor the provision of the service by the municipality and third parties influences waste collection, at least at the aggregate level. When grouping municipalities according to population size, different results were obtained. The significant variables differ between groups: as the population size per municipality decreases, participatory budgets tend to be significant in explaining the volume of solid waste collected, in the sense that it has no impact on large municipalities but has an impact on micro municipalities. Larger population municipalities face greater difficulties in fostering citizen participation, which in turn exacerbates the challenges associated with service delivery. In large municipalities, the quality of the objectives in territorial planning has an inverse influence, which can be explained by the fact that the TODP priorities are oriented towards other areas. In medium-sized municipalities, there is an inverse relationship with fiscal dependence, participation mechanisms and accountability, which are the result of prioritising other municipal competencies, such as security or access to drinking water. The

implementation of ordinances and the reliance on municipal service delivery in smaller municipalities significantly bolster solid waste collection efforts. Furthermore, citizen involvement through control mechanisms in small municipalities and participatory budgeting in micro municipalities plays a crucial role in this enhancement. These findings perhaps show that as the size of municipalities decreases, citizen participation is relevant in community management. With respect to SWM value chain services, discrete choice panel data models were estimated for all municipalities. In the context of storage, transfer, recovery, and disposal, random effects models were chosen based on the acceptance of the null hypothesis from the Hausman test. Conversely, fixed effects models were applied specifically for the provision of collection. The marginal effects in terms of partial derivatives of these estimates are shown in Table 5.

The estimates of service provision probabilities in the SWM value chain did not take into account the gross value added from production, as it was found to be statistically insignificant across all evaluations. Reasons may consider that the service is provided by the municipality and depends on fiscal resources (Plata-Díaz *et al*., 2014), it is the population and urbanisation that determines waste generation (Cheng *et al*., 2020) or the service charging policy (Magazzino *et al*., 2020). The findings indicate that only the existence of by-laws regulating waste management was statistically significant for the probability of providing waste collection services and the probability increases by 52.96% when by-laws are in place. Regarding the storage or temporary disposal of waste for transport, no significant variables were identified since this is one of the services that is provided by a smaller proportion, as is the transfer to recovery or treatment. When considering the probability of executing the transfer service, it is observed that superior quality of the TODP indicators and diminished fiscal reliance enhance this probability. In contrast, increased efficiency in financial allocation, a more inclusive budgetary process, and the establishment of ordinances are associated with a lower probability of service provision. This trend reflects the lack of sufficient regulatory frameworks governing the services within the value chain, aside from the collection aspect. Waste recovery or treatment, which includes recycling, increases the likelihood of provision as fiscal dependence (central government resources) decreases and there are ordinances for regularisation and control. The implementation of ordinances significantly raises the chances of executing final disposal services, which entail the deposition of waste in locations designed to minimize environmental and health impacts, such as sanitary landfills. Additionally, the collection services, regulated by these ordinances, are characterized as the most structured and formalized services in this context. In spite of this, the probability of providing the final disposal service diminishes as dependence on the central government decreases. The disparity between waste generation and waste collection is concerning, particularly given that waste collection is a service subsidized by municipal governments. However, the situation becomes increasingly alarming when examining other components of the waste management value chain, notably in storage, transfer, and utilization services. These aspects lack regulatory frameworks and are predominantly managed by informal operators. Collection and disposal services have the highest coverage (over 90% on average) and are foreseen in the different municipal ordinances, which largely explains the results in terms of collection volume and the likelihood of providing both services. In smaller municipalities, as noted by Putnam (1993) and Bourdieu (1985), levels of social capital and proximity between citizens and local governments facilitate more direct and participatory interaction. This "social capital", encompassing relationships of trust and reciprocity, enhances the efficiency of managing public goods like solid waste. The smaller scale of the population allows participatory mechanisms, such as participatory budgeting or neighbourhood committees, to be more effective, translating into a better capacity to respond to local needs. Research by Guerrero *et al*. (2013) also supports this view, highlighting that in smaller municipalities, citizen participation is key to the success of recycling programmes and other aspects of SWM. The intimate relationship between citizens and local authorities fosters a spirit of cooperation and supports the oversight of regional policy implementation. The implementation of community recycling programmes and environmental education tends to be more effective when citizens are actively involved in the creation and management of projects

. Conversely, larger municipalities tend to experience more limitations regarding citizen participation. The increased bureaucracy and administrative complexity inherent in these settings contribute to the difficulties encountered in the successful execution of participatory mechanisms. Houwelingen (2017) points out that as population size increases, the ability of local institutions to foster participation diminishes, as the distance between citizens and decision-makers grows. Findings from Benito *et al*. (2021) reinforce this viewpoint, revealing that municipal governments in more populous cities confront a range of complex challenges. These challenges include heightened service demands and the requirement for coordination among multiple entities, which subsequently weakens the role of citizen participation in shaping management outcomes. Additionally, the greater diversity of problems and priorities in larger municipalities means that waste management must compete with other pressing issues, such as security or access to basic services, limiting the attention that can be devoted to citizen participation in SWM. McDonnell (2019) also notes that political efficacy and satisfaction with public services decline as the size of the municipality increases, which can lead to lower participation and, consequently, less influence on waste management outcomes. The study's findings suggest that innovations in SWM in smaller municipalities are closely linked to citizen participation. The establishment of community recycling facilities and the promotion of composting projects serve as notable instances of how local communities can effectively spearhead SWM efforts. These efforts are strengthened by citizen involvement, which, as noted by UN-Habitat (2010), is essential for promoting responsible behaviour in waste management. The engagement of citizens in local governance facilitates the implementation of more sustainable initiatives that are specifically designed to meet the needs of the community, including programs focused on environmental education and awareness. Regarding fiscal management, financial sustainability remains a challenge in smaller municipalities, as dependence on external funding is high. Bartolacci *et al*. (2018) highlight the importance of efficient and transparent fiscal management in local governments, including optimising revenue and expenditures related to SWM services. Introducing innovative funding strategies, such as public-private partnerships and pay-as-you-go systems for waste generation, may significantly bolster the financial feasibility of these services, particularly in smaller municipalities with limited resources. This study aligns with previous research that underscores the key role of citizen participation in SWM. Specifically, studies such as those by Aprilia *et al.* (2011) and Masood *et al.* (2014) have demonstrated that active citizen engagement in waste management contributes to greater efficiency and sustainability, particularly in smaller municipalities. These studies also emphasise that environmental education and awareness are essential for the success of SWM policies, which is reflected in the findings of this study. However, this study contributes new insights by showing that in larger municipalities, citizen participation does not have a significant impact on waste collection. This observation diverges from the conclusions drawn by Wu *et al*. (2020), who argue that citizen participation is consistently significant, regardless of the size of the municipality. The results of this study indicate that waste management in larger municipalities depends more on financial and structural factors, such as fiscal sustainability and the presence of regulations, than on citizen participation. The study provides new findings on the relationship between fiscal sustainability and the provision of SWM services. Municipalities that diminish their reliance on external financial resources tend to experience enhanced effectiveness in waste collection efforts. This finding implies that local governments should actively pursue opportunities to broaden their revenue bases and lessen their dependence on central government funding, which would further promote greater independence in the management of public services.

CONCLUSION

The study provides an in-depth analysis of how municipal administration, public participation, and the implementation of ordinances affect the processes of solid waste collection and the feasibility of delivering services across the value chain, encompassing storage, transfer, recovery, and final disposal. It specifically targets 221 municipalities in Ecuador over the period from 2017 to 2022, utilizing panel data models to elucidate the influence among critical variables. One of the most relevant findings of the study is that citizen participation has a significant

impact in smaller municipalities, where the proximity of the community and local administration allows for more direct interaction. Mechanisms such as participatory budgeting and social control enable citizen participation to affect solid waste collection processes. In contrast, this influence is often less visible in larger municipalities, which may be attributed to the challenges posed by administrative complexity and bureaucratic systems that limit the capacity for effective citizen involvement. Participation is influenced to the extent that it is mediated by the size of the locality. It is also affected by the existence of by-laws and reliance on the municipality providing collection services. In the case of larger municipalities, none of these relationships are evident, since their governance is managed by third-party organizations, such as public enterprises or coalitions of municipalities. In terms of financial management, the importance of fiscal dependence and financial sustainability should be highlighted, as it is a subsidised service that involves budgetary outlays of close to 50% of the amount of the service. Overall, the planning aspect does not appear to make a substantial impact on the volume of collections or the delivery of other. The likelihood of providing the value chain services associated with storage, transfers and recovery, being the least regulated, is affected by fiscal dependency and the existence of ordinances, with no evidence of the influence of citizen participation. In Ecuador, solid waste management is an area that is progressing, having made considerable strides, yet it still grapples with critical challenges. The resolution of these issues is contingent upon the development of a comprehensive regulatory framework and the embrace of sustainable practices. Its long-term success is associated with the capacity of municipalities to implement these policies, the improvement of infrastructure and active citizen participation. The study adds significant scientific value by demonstrating how financial management, including fiscal sustainability and dependence on external funding, plays a critical role in the effectiveness of SWM services. While this relationship has been previously explored in academic discourse, the present study contributes fresh empirical insights, particularly relevant to the Ecuadorian setting, where local governments grapple with specific challenges stemming from decentralization and limited financial resources. The findings have practical implications for policymakers; the results suggest that municipalities, particularly those with smaller populations, should focus on strengthening participatory mechanisms, such as participatory budgeting and community oversight, to improve SWM outcomes. The study indicates that in larger municipalities, where the effect of citizen engagement is often limited, it is advisable to prioritize innovations in financial management and regulatory frameworks to bolster the quality of service provision. One of the key contributions of this study is its focus on the differing roles of citizen participation and financial management across municipalities of varying sizes. Unlike previous studies that typically addressed these factors in isolation or in a generalised context, this research offers a more nuanced analysis, revealing how municipal size mediates the effectiveness of these factorsThrough the application of a panel data analysis encompassing various municipalities in Ecuador over an extended period, this study offers substantial empirical evidence advocating for the formulation of customized solid waste management policies that cater to municipalities of varying sizes. The research also contributes to the literature by identifying that, while citizen participation is effective in smaller municipalities, financial sustainability and the presence of ordinances are more decisive in larger municipalities. This distinction is crucial for crafting policies that address the unique challenges faced by both types of municipalities. The findings are highly applicable in the context of local governance and environmental policy, particularly in developing countries where decentralised governance and financial constraints are common. This study offers critical insights that policymakers can leverage to develop solid waste management policies that are more effectively aligned with the unique needs and operational capacities of municipalities of various sizes. For instance, smaller municipalities can be encouraged to develop community-driven initiatives with strong participatory mechanisms, while larger municipalities should focus on improving fiscal management and regulatory compliance to optimise waste management services. Moreover, the analysis points to the significance of creating clear and structured guidelines to manage all aspects of the SWM value chain, which should encompass more than just the processes of collection and final disposal. This approach has the potential to lessen informal

practices and bolster the provision of services, including waste storage and transfer, which are commonly deficient in Ecuador and analogous contexts. Several constraints have been identified within the study that may impact the interpretation of its outcomes: 1) the study is centered on data derived from Ecuador, which could potentially limit the extent to which the findings can be generalized to other countries characterized by different governance systems, socio-economic environments, or cultural norms related to waste management. Concequently, while the outcomes are particularly pertinent to Ecuador and may extend to other Latin American countries, it is important to approach the application of these findings to regions with substantially different contexts with a degree of caution.; 2) while the study examines the impact of municipal size on SWM effectiveness, other factors such as geographic location, urbanisation levels, and cultural attitudes towards waste were not fully explored, 3) the study predominantly utilizes quantitative panel data to evaluate the connections among citizen engagement, financial management, and SWM. However, it does not delve deeply into qualitative factors, such as the motivations behind citizen participation or the local political dynamics that could affect the implementation of SWM policies. Subsequent studies might consider employing qualitative approaches to enhance the depth of understanding regarding these influences; 4) since the data on municipal operational capacity and citizen participation were gathered from official sources, there is a possibility of reporting bias. Municipalities may overstate their operational capacity or the effectiveness of participatory mechanisms to align with national guidelines or reporting standards. The limitations highlighted suggest that, while the study yields important insights, its conclusions ought to be contextualized within the particular governance and socio-economic framework of Ecuador. Future research could address these limitations by expanding the geographic scope to include municipalities from other countries, examining the influence of other factors such as urbanisation and local governance practices, and incorporating qualitative data to provide a more holistic analysis of SWM challenges and solutions. Although there are certain limitations, this study represents a substantial advancement in the literature concerning SWM and decentralized governance. It delivers valuable insights that can assist policymakers and local authorities in their efforts to optimize the efficiency and sustainability of waste management systems.

AUTHOR CONTRIBUTIONS

P. Hernández-Medina, the corresponding author, has contributed in the data analysis OCI and solid waste, interpreted the results, and preparing the manuscript. D. Pinilla-Rodríguez prepared all the figures and interpretation of the results.

ACKNOWLEDGEMENT

The study has not received funding.

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

©2024 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
CNC	Ecuador's National Council of Competencies
CPC	Citizen participation council
COOTAD	Organic Code of Territorial Organisation, Autonomy and Decentralisation
DAGs	Ecuador's decentralised autonomous governments
FE	fixed effects
GFI	Goal fulfilment index
GLS	Generalised least squares
INEC	Institute of Statistics and Censuses
Kg	Kilograms
NPIMSW	National Programme for the Integrated Management of Solid Waste
OCI	Operational Capacity Index
RE	Random effects
SWM	Solid waste management
TODPs	Territorial order and development plans
Wald chi²	Goodness-of-fit test (overall significance of explicative variables)
Hausman	Hausman test for fixed or random effects selection
R^2 overall	Proportion that the model can explain of the variability of the dependent variable
R^2 within	Proportion of the variability of the dependent variable over time that the model is able to explain
R^2 between	Proportion that the model is able to explain of the variability of the dependent variable across municipalities
Rho	Represents the proportion of the variance that is due to differences across municipalities

REFERENCES

Alvarado-Ibarra, J.; Ochoa-Cabrera, K.; Burrola-Núñez, H., (2024). Reciclacentros: iniciativa de gestión sostenible de los residuos sólidos urbanos en una ciudad mexicana. Revista Facultad de Ingenieria. 111: 48-54 (**7 pages**).

Angouria-Tsorochidou, E.; Teigiserova, D.; Thomsen, M., (2022). Environmental and economic assessment of decentralized bioenergy and biorefinery networks treating urban biowaste. Resour. Conserv. Recycl., 176: 1-11 (**11 pages**).

Aprilia, A., Tezuka, T.; Spaargaren, G., (2011). Municipal solid waste management with citizen participation: an alternative solution to waste problems in Jakarta, Indonesia. In: Yao, T. (eds) Zero-Carbon Energy Kyoto 2010. Green Energy and Technology. Springer, Tokyo: 56-62 (**7 pages**).

Bartolacci, F.; Paolini, A.; Quaranta, A.; Soverchia, M., (2018). Assessing factors that influence waste management financial sustainability. Waste Manage., 79: 571-579 (**9 pages**).

Batista, M.; Caiado, R.; Quelhas, O.; Lima, G.; Filho, W.; Yparraguirre, I., (2021). A framework for sustainable and integrated municipal solid waste management: barriers and critical factors to developing countries. J. Cleaner Product., 312: 127516 (**14 pages**).

Benito, B.; Guillamón, M.; Martínez-Córdoba, P.; Ríos, A., (2021). Influence of selected aspects of local governance on the efficiency of waste collection and street cleaning services. Waste Manage., 126: 800-809 **(10 pages).**

Bernache-Pérez, G.; Medina-Salas, L.; Castillo-González, E.; Giraldi-Díaz, M., (2023). Strategies to strengthen integrated solid waste management in small municipalities. Sustainability. 15(5): 4318 (**13 pages**).

Bernal, R.; Sánchez, E.; Mauricio, D.; Raymundo, C., (2020). Comprehensive management model for solid waste collection and transportation in Peruvian urban municipalities. Huma. Interact. Emerg. Technol., 1018: 959-966 (**8 pages**).

Bourdieu, P., (1985). The forms of capital. En J. Richardson. Handbook of theory and research for the sociology of education). New York, United States: Greenwood. 241-258 **(18 pages).**

Burneo, D.; Cansino, J.; Yñiguez, R., (2020). Environmental and socioeconomic impacts of urban waste recycling as part of circular economy. The case of Cuenca (Ecuador). Sustainability. 12(8): 3406 (**22 pages**).

Campos-Alba, C.; Garrido-Rodríguez, J.; Plata-Díaz, A.; Pérez-López, G., (2021). The selective collection of municipal solid waste and other factors determining cost efficiency. An analysis of service provision by spanish municipalities. Waste Manage., 134: 11-20 (**10 pages**).

Carmen-Niño, V.; Herrera-Navarrete, R.; Juárez-López, A., Sampedro-Rosas, M.; Reyes-Umaña, M., (2023). Municipal solid waste collection: challenges, strategies and perspectives in the optimization of a municipal route in a Southern Mexican Town. Sustainability. 15(2): 1083 (**15 pages**).

Cheng, J.; Shi, F.; Yi, J.; Fu, H., (2020). Analysis of the factors that affect the production of municipal solid waste in China. J. Cleaner Product., 259: 120808 (**11 pages**).

Chicaiza, C.; Navarrete, V.; Camacho, C.; Chicaiza, Á., (2020). Evaluation of municipal solid waste management system of Quito – Ecuador. LALCA: Revista Latino-Americana Em Avaliação Do Ciclo De Vida, 4: 1-13 (**14 pages**).

Consejo Nacional de Competencias, (2019). Informe sobre mapeo de actores generadores de información a nivel territorial e identificación de la competencia de desechos sólidos. Dirección de Monitoreo y Evaluación a Gobiernos autónomos descentralizados: QUITO.

Consejo Nacional de Competencias, (2023). Ficha metodológica Plan Nacional de Desarrollo 2023-2025. Dirección de Monitoreo y Evaluación: QUITO.

Consejo Nacional de Competencias, (2024). Indice de capacidad operativa-componente total. Dirección de Monitoreo y Evaluación: QUITO.

De Oliveira, C.T.; Bonfante, M.C.; Maldonado, M.U.; Soares, S.R., (2023). Continuing education to food waste management: a system dynamics simulation. Revista Brasileira de Gestao e Desenvolvimento Regional. 19(2): 484-506 (**23 pages**).

Díaz-Barriga-Fernandez, A.; Santibañez-Aguilar, J.; Radwan, N.; Nápoles-Rivera, F.; El-Halwagi, M.; Ponce-Ortega, J., (2017). Strategic planning for managing municipal solid wastes with consideration of multiple stakeholders. ACS Sustainable Chem. Eng., 44: 10744-10762 (**19 pages**).https://doi.org/10.1021/ACSSUSCHEMENG.7B02717

Doussoulin, J.; Colther, C., (2022). Evaluating the efficiency of municipal solid waste collection services in developing countries: the case of Chile. Sustainability. 14(2): 15887 (**19 pages**).

Ferronato, N.; Ragazzi, M.; Portillo, M.; Lizarazu, E.; Viotti, P.; Torretta, V., (2019). How to improve recycling rate in developing big cities: an integrated approach for assessing municipal solid waste collection and treatment scenarios. Environ. Dev., 29: 94-110 (**17 pages**).

Foucart, R.; Wan, C., (2017). Strategic decentralization and the provision of global public goods. J. Environ. Econ. Manage, 92: 537-558 (**22 pages**).

Ghiani, G.; Manni, A.; Manni, E.; Toraldo, M., (2014). The impact of an efficient collection sites location on the zoning phase in municipal solid waste management. Waste Manage., 34(11): 1949-1956 (**8 pages**).

Guerrero, L.; Maas, G.; Hogland, W., (2013). Solid waste management challenges for cities in developing countries. Waste Manage., 33(1): 220-232 (**13 pages**).

Houwelingen, P. (2017). Political participation and municipal population size: a meta-study. Local Government Studies. 43: 408-428 (**21 pages**).

INEC, (2023). Estadística de información ambiental económica en gobiernos autónomos descentralizados municipales. Gestión de residuos sólidos 2022. Instituto Nacional de Estadística y Censos: QUITO.

Jomehpour, M.; Behzad, M., (2020). An investigation on shaping local waste management services based on public participation: a case study of Amol, Mazandaran Province, Iran. Environ. Dev., 35: 100519 (**16 pages**).

Kala, K.; Bolia, N.B., (2021). Analysis of citizen's perception towards segregation and composting. Environ. Dev. Sustainability. 23(7): 10763-10786 (**14 pages**).

Kiguli, D.; Nabukonde, A.; Barakagira, A., (2023). Compliance and implementation of municipal solid waste management laws and regulations in Mukono District, Uganda. Arch. Curr. Res. Int., 23(7): 194-204 (**11 pages**).

Lohri, C.; Camenzind, E.; Zurbrügg, C., (2014). Financial sustainability in municipal solid waste management-costs and revenues in Bahir Dar, Ethiopia. Waste Manage., 34(2): 542-552 (**11 pages**).

Magazzino, C.; Mele, M.; Schneider, N., (2020). The relationship between municipal solid waste and greenhouse gas emissions: Evidence from Switzerland. Waste Manage., 113(15): 508-520 (**13 pages**).

Masood, M.; Barlow, C.Y.; Wilson, D.C., (2014). An assessment of the current municipal solid waste management system in Lahore, Pakistan. Waste Manage. Res., 32(9): 834-847 (**14 pages**).

McDonnell, J., (2019). Municipality size, political efficacy and political participation: a systematic review. Local Govern. Stud., 46(3): 331 – 350 (**20 pages**).

McDonnell, J., (2022). Municipality size and political participation: evidence from Australia. Aust. J. Polit. Sci., 58(1): 70 – 87 (**18 pages**).

Ministerio del Ambiente, (2015). Diagnóstico de la cadena de gestión integral de desechos sólidos-reciclaje. Secretaría Técnica del Comité Interinstitucional para el Cambio de la Matriz Productiva-Vicepresidencia del Ecuador: QUITO.

Montero, R., (2011). Efectos fijos o aleatorios: test de especificación. Documentos de Trabajo en Economía Aplicada. Universidad de Granada. España.

Nhubu, T.; Muzenda, E.; Mohamed, B.; Mbohwa, C., (2021). Framework for decentralizing municipal solid waste management in Harare, Zimbabwe. Adv. Sci. Technol. Eng. Syst. J., 6(2): 1029-1037 (**9 pages**).

Plata-Díaz, A.; Zafra-Gómez, J.; Pérez-López, G.; López-Hernández, A., (2014). Alternative management structures for municipal waste collection services: the influence of economic and political factors. Waste Manage., 34(11): 1967-1976 (**10 pages**).

Pérez-López, G.; Prior, D., Zafra-Gómez, J.; Plata-Díaz, A., (2016). Cost efficiency in municipal solid waste service delivery. Alternative management forms in relation to local population size. Europ. J. Operational Res., 255(2): 583-592 (**10 pages**).

Pinha, A.; Sagawa, J., (2020). A system dynamic modelling approach for municipal solid waste management and financial analysis. J. Cleaner Product., 269: 1-50 (**50 pages**).

Pinnawala, M., (2016). Community participation in solid waste management: The case of Kurunagala municipal council in the northwestern province of Sri Lanka. Malays. J. Sci., 35(2): 63-72 (**10 pages**).

Putnam, R., (1993). What makes democracy work? National Civic Review, 101-107 (**7 pages**).

Raghu, S.J.; Rodrigues, L.L.R., (2021). A concept of solid waste management behaviour in India – a solution towards environmental sustainability. Quality - Access to Success. 22(183): 155-162 (**8 pages**).

Ranjith, L.A.S.; Chowdhury, F.J., (2007). Alumni of an educational institute as change agents for community-based environmental management initiatives: experience from a solid waste management demonstration project in Hanoi, Vietnam. Int. J. Environ. Technol. Manage., 7(3/4): 392-406 (**15 pages**).

Romano, G.; Molinos-Senante, M., (2020). Factors affecting eco-efficiency of municipal waste services in Tuscan municipalities: an empirical investigation of different management models. Waste Manage., 105: 384-394 (**11 pages**).

Rondinelli, D.A.; Nellis, J.R.; Cheema, G.S., (1989). Decentralization in developing countries: a review of recent experience. World Bank Staff Working Papers, No. 581.

Tsypkin, Y.A.; Kamaev, R.A.; Bliznukova, T.V.; Pakulin, S.L.; Feklistova, I.S.m, (2020). Improving the control of municipal solid waste management processes in the region. In: Kolmykova, T., Kharchenko, E. (eds) Digital Future Economic Growth, Social Adaptation, and Technological Perspectives. Lecture Notes in Networks and Systems. Springer, Cham: 747-759 (**13 pages**).

UN-Habitat, (2010). Solid waste management in the World's Cities.

London: United Nations Human Settlements Programme.
Villalba Ferreira, M.; Dijkstra, G.; Scholten, P.; Sucozhañay, D., (2022). The effectiveness of inter-municipal cooperation for integrated sustainable waste management: a case study in Ecuador. Waste Manage., 150: 208-217 (**10 pages**).
Wooldridge, J., (2010). Econometric Analysis of Cross Section and Panel Data. MIT Press.
Wu, L.; Ma, T.; Bian, Y.; Li, S.; Yi, Z., (2020). Improvement of regional environmental quality: government environmental governance and public participation. Sci. Total Environ., 717: 187265 (**12 pages**).
Yukalang, N.; Clarke, B.; Ross, K, (2017). Barriers to effective municipal solid waste management in a rapidly urbanizing area in Thailand. Int. J. Environ. Res. Public Health. 14(4): 1013 (**23 pages**).
Zaman, A., (2024). Assessment of solid waste management practices in rural Bangladesh: a Case study of citizen participation. Res. Agric. Livest. Fish. 10(3): 301–318 (**18 pages**).
Zhang, Z.; Chen, Z.; Zhang, J.; Liu, Y.; Chen, L.; Yang, M.; Osman, A. I.; Farghali, M.; Liu, E.; Hassan, D.; Ihara, I.; Lu, K.; Rooney, D. W.; Yap, P.S., (2024). Municipal solid waste management challenges in developing regions: a comprehensive review and future perspectives for Asia and Africa. Sci. Total Environ., 930: 172794 (**17 pages**).

AUTHOR (S) BIOSKETCHES

Hernández- Medina, P., Ph.D., Professor, Department of Economics, Universidad Nacional de Chimborazo, Riobamba, Chimborazo, Ecuador.
▪ Email: *patricia.hernandez@unach.edu.ec*
▪ Web of Science ResearcherID: NA
▪ ORCID: 0000-0001-8527-5158
▪ Scopus Author ID: 57212575001
▪ Homepage: https://www.unach.edu.ec/economia-ele/; https://scholar.google.com/citations?user=_ZRk5AwAAAAJ&hl=en

Pinilla-Rodríguez, D., Ph.D., Professor, Department of Economics, Universidad Nacional de Chimborazo, Riobamba, Chimborazo, Ecuador.
▪ Email: *dpinilla@unach.edu.ec*
▪ ORCID: 0000-0002-6663-9478
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 55962551700
▪ Homepage: https://www.unach.edu.ec/economia-ele/; https://scholar.google.es/citations?user=WNIh_hoAAAAJ&hl=es

HOW TO CITE THIS ARTICLE

Hernández-Medina, P.; Pinilla-Rodríguez, D., (2023). Municipal panel data analysis for solid waste, local governments and citizen participation. Global J. Environ. Sci. Manage., 10(SI): 105-122.

DOI: 10.22034/gjesm.2024.10.SI.07

URL: https://www.gjesm.net/article_715703.html

Global J. Environ. Sci. Manage. 10(SI): 123-136, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH ARTICLE

Characterization of shallow groundwater in coastal aquifer of urbanized area using stable isotope and hydrochemical approaches

S. Satrio, R. Prasetio*, E.R. Pujiindiyati, M.F. Ramadhani, P. Sidauruk

Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia

ARTICLE INFO

Article History:
Received 22 May 2024
Revised 25 July 2024
Accepted 30 September 2024

Keywords:
Cirebon
Hydrochemistry
Salinization
Shallow groundwater
Stable isotope

ABSTRACT

BACKGROUND AND OBJECTIVES: Cirebon City, located in West Java, Indonesia, is one of the coastal cities formed from alluvial deposits with aquifer rocks in form of gravels and sands in the plains, as well as sands in the hills. Due to its urbanized nature, the city experiences a substantial need for access to clean water. A significant number of residents remain reliant on drinking water providers for safe water, given the contamination of seawater in specific regions, while some continue to draw from shallow groundwater. As groundwater abstraction can intensify seawater intrusion, especially in urbanized area, it is important to investigate this matter. This study sought to qualitatively and quantitatively analyze the degree of seawater pollution affecting the shallow groundwater in Cirebon City, Indonesia.
METHODS: Water samples were collected from 44 shallow groundwater wells around Cirebon City. Following collection, the samples were examined for their significant water chemistry content using ion chromatography and for their isotopic composition through a liquid water isotope analyzer. Interpretation was done using graphical tools such as Piper and scatter diagrams, as well as mathematical equation to approximate mixing proportion between fresh groundwater and seawater and its proportion.
FINDINGS: Stable isotope analysis revealed that eight shallow groundwater samples were salinized due to the incorporation of seawater, with the proportion of seawater ranging from approximately 17.3 to 54.9 percent. These samples have very enriched oxygen-18 isotope composition values up to-3.9 permil. Another 14 samples were mixed with surface water, and the remaining 22 samples were fresh groundwater. Analysis of the hydrochemical properties indicates that fresh shallow groundwater primarily exhibits a bicarbonate composition. In contrast, the salinized shallow groundwater is identified as sodium chloride type, with chloride concentrations reaching a maximum of 6980 milligrams per liter and sodium concentrations peaking at 4963 miligrams per liter. Salinized shallow groundwater samples were up to 1.5 kilometer inland from coastline, which can be considered as an environmental concern.
CONCLUSION: The seawater contamination into shallow aquifer have reached up to 1.5 kilometer inland and with seawater proportion is up to 55 percent. Throughout the contamination process, the chemical composition of groundwater is modified not solely due to mixing, but also as a result of ion-exchange mechanisms. The significant rate of seawater contamination necessitates urgent action from all stakeholders, with local government leadership being essential. To effectively address this problem, it is vital to limit the extraction of shallow groundwater by enhancing the capabilities of the government's water piping services and to either slow down or completely halt the advancement of seawater intrusion through the adoption of artificial groundwater recharge strategies.

DOI: 10.22034/gjesm.2024.10.SI.08

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

NUMBER OF REFERENCES
38

NUMBER OF FIGURES
7

NUMBER OF TABLES
3

*Corresponding Author:
Email: *rasi.prasetio@brin.go.id*
Phone: +62813 2256 1062
ORCID: 0000-0002-6682-653X

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Cirebon City, located in West Java, Indonesia. The city evolved from old settlements built on alluvial deposits. Cirebon is one of the most important cities on the north coast of the island of Java. The rapid expansion of industrial, commercial, and tourism activities in the city have significantly escalated the demand for clean water. Fasa *et al*. (2022) indicate that around 31.6 percent of this water is supplied through water piping services, with the remainder sourced. Excessive abstraction of groundwater has given an extra pressure to groundwater quality especially near the coastal line. Some groundwater especially near the coast categorized as brackish to saline water. In this region, the water table is found at a 2 – 6 meters (m) depth below the surface Moving away from the shoreline, the depth of groundwater ranges from 5 to 10 m, exhibiting a comparatively higher quality. In the southern hilly regions, the most favorable groundwater quality is identified at depths of 20 to 30 m. There has been an increase in the salinization of shallow groundwater in several locations around the coastal area, namely Kejaksan, Pekalipan, and Lemahwungkuk regions. An increase in salinization has been detected in various shallow groundwater wells in the vicinity of the city's coastline. The groundwater salinization in coastal area is caused by factors such as mineral weathering, water-rock interaction (Gassama *et al*., 2011), seawater intrusion (Lu and Werner, 2013) and can be intensified by over-exploitation of groundwater (Mas-Pla *et al.,* 2012). Previous studies showed that Cirebon coastal line is not only facing land subsidence threat (Bramanto *et al*., 2023), but it is also under the threat of shifting into the land due to increasing sea level and abrasion (Pratama *et al*., 2023). These factors may further exacerbate the issue of seawater intrusion (Rositasari *et al*., 2011).

Geology of cirebon, West Java

Fig. 1 shows a geological map of the Cirebon area. Geologically, Cirebon is located on sedimentary alluvial deposits (Qa) facies consisting of gravel, sands, and clay deposits with a thickness of up to 5 m. Meanwhile, the coastal line comprises of coastal sediments (Qac), which consists of marsh sediment,

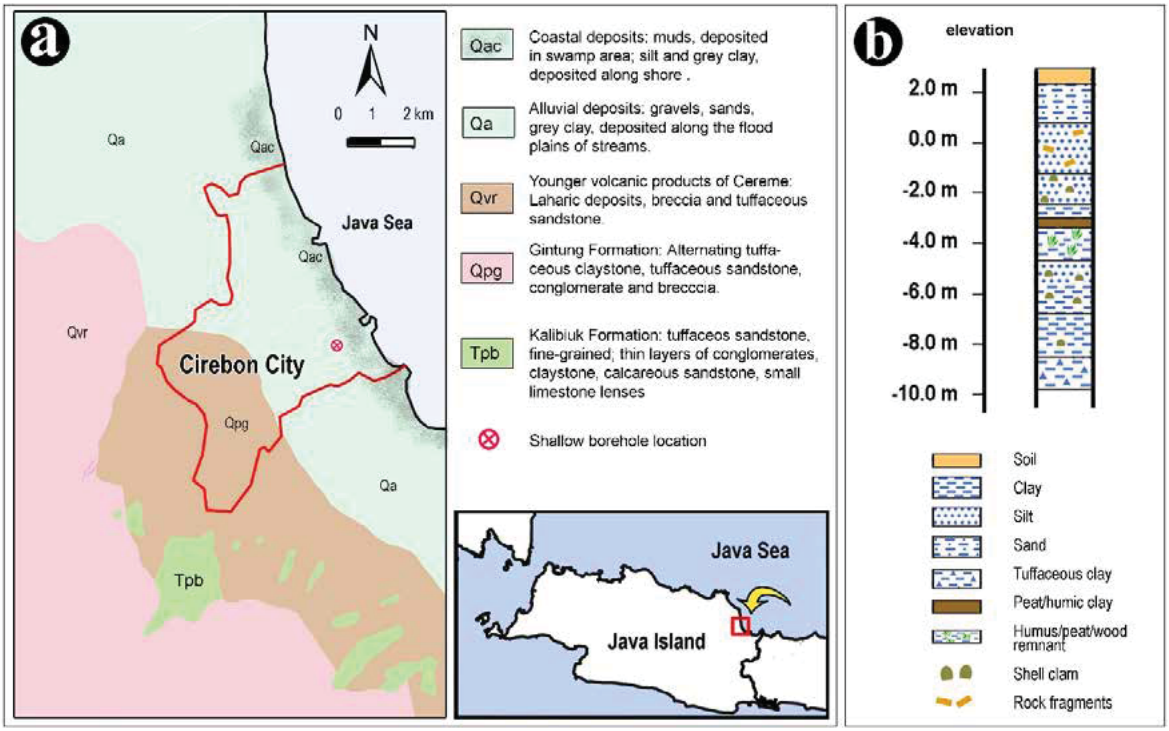


Fig. 1: (a) Geological map of Cirebon region (b) Lithological profile of shallow borehole (Hidayat *et al*., 2009; Silitonga *et al.,* 1996)

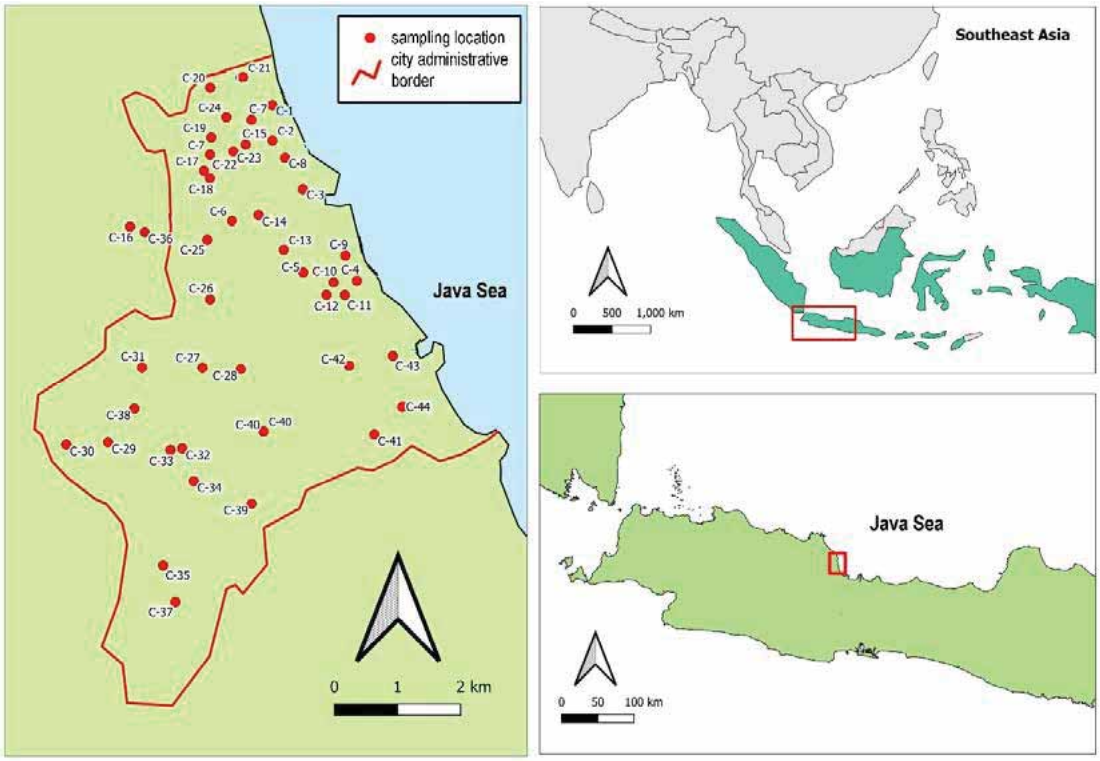


Fig. 2: Geographic location of the study area and sampling location in Cirebon City, West Java, Indonesia (Sampling indicated with red circle marks)

silt, and clay exhibiting a thickness of several meters. In the higher area of Cirebon, Gintung Formation (Qpg) dominates the terrain, consisting of alternating tuffaceous claystone, tuffaceous sandstone, conglomerate, and breccia (Silitonga *et al*., 1996).

According to stratigraphic findings, the alluvial plain is classified into three sedimentation stages, which are determined by fluctuations in sea level: a high sea level phase, a phase of decreasing sea level, and a low sea level. These processes were triggered by changes in environmental conditions and the tectonic activities within the region (Ezquerro *et al*., 2019). While in the study area, sediment succession is divided into three sedimentation intervals which each intervals represents environmental changes due to changes of sea level (Hidayat *et al*, 2009). The groundwater challenges faced by Cirebon City necessitate the implementation of investigations employing isotope and hydrochemical techniques. These methods are essential for collecting data and delineating the properties of shallow groundwater, in addition to assessing the extent of seawater intrusion within the coastal aquifer of Cirebon. This study aimed to qualitatively and quantitatively assess the extent of seawater contamination to shallow groundwater in Cirebon City. The sampling campaign was done in 2022, collecting 44 shallow groundwater samples (Fig. 2) in Cirebon City from the coastline up to about 6 kilometers (km) inland (108.532° – 108.582° East and 6.694° – 6.769° South). Due to the private ownership of the shallow wells by local residents, there exists a lack of lithological documentation and information concerning the depth of the water table.

MATERIALS AND METHODS

There were 44 samples collected during this study. The samples were collected from existing wells located in the vicinity of Cirebon city. The collected samples were then sent to the Center of Research and Technology Radiation Process Laboratory, National Research and Innovation Agency (BRIN) in Jakarta which is about 150 km from the study area.

Water sampling

Groundwater and seawater samples were collected into 20 milliliter (mL) plastic bottles each. It is essential that the bottles are entirely filled with water, devoid of any air bubbles, and securely closed to inhibit evaporation (Wijatna *et al*., 2019). For the analysis of anions and cations, water samples were collected in individual bottles, each with a capacity of 500 mL. To prevent the precipitation of cation samples and to ensure the stability of bacterial activity during shipping and storage, it is necessary to add several drops of concentrated (68%) pro analysis (pa) nitric acid (HNO3) (Sanchez, *et al*., 2017; Satrio *et al*., 2021). To prevent contamination and to minimize evaporation, biological or chemical changes, samples were stored in clean and chemically inert containers (i.e., polyethylene bottles), and cooled below ambient temperatures, respectively (F. Liu *et al*., 2019).

Water sample analysis

The stable isotope contents of oxygen-18 (^{18}O) and hydrogen-2 (^{2}H) were measured using Liquid Water Isotope Analyzer - Los Gatos Research (LWIA-LGR). The instrument measures the isotopic ratio of oxygen-18 to oxygen-16 ($^{18}O/^{16}O$) and hydrogen-2 to hydrogen-1 ($^{2}H/^{1}H$), with respect to Vienna Standard Mean Oceanic Water (VSMOW) standard to obtain its d value. The isotopic composition of water samples is represented by a delta value (δ) in parts per thousand, known as permil (‰), following the formulation provided in Eq. 1 (Gourcy *et al*., 2005):

$$\delta = \frac{(R_{sample} - R_{SMOW})}{R_{SMOW}} \times 1000‰ \quad (1)$$

Where, R_{sample} and R_{SMOW} are ratio of $^{2}H/^{1}H$ or $^{18}O/^{16}O$ and ratio of $^{2}H/^{1}H$ or $^{18}O/^{16}O$ in sample and standard reference SMOW. Chemistry analysis was performed using the Metrohm ion chromatography system. For anions analysis, a Metrosep A Supp 5 column was used with carbonate-bicarbonate eluent (Merck, pa). The cation analysis was performed using a Metrosepp C4 column, with dipicolinic acid (Merck, pa) as the eluent. Sample analyses were performed at the Center of Research and Technology Radiation Process Laboratory, National Research and Innovation Agency (BRIN).

Data interpretation

Natural stable isotope such as ^{18}O and ^{2}H were employed to study groundwater characteristics and its origin (Aksever and Davraz, 2018; Sidibé *et al*., 2019). These isotopes functioned as unique identifiers to differentiate between various water sources, including groundwater, rainwater, seawater, surface water, or any combinations thereof. The analysis of isotopic data and the chemical properties of groundwater was applied to investigate the challenge posed by seawater encroachment. Isotope ^{18}O value exhibits correlations with chloride (Cl), electrical conductivity (EC), and sulfate (SO_4) (Ersoy *et al*., 2021). In the context of hydrological studies, the isotopes present in water molecules are utilized as effective tracers to ascertain the source and progression of water throughout the soil layers (Tweed *et al*., 2020). Data on ^{18}O and ^{2}H isotopes, along with water chemistry data, were utilized to obtain information on the salinization process in Cirebon coastal aquifer. Meanwhile, major hydrochemical ions were applied to classify natural water into types and mixtures, such as distinguishing between fresh water and seawater (Vasu *et al*., 2017). The mass balance equation (Eq. 2) was employed to compute the percentage of seawater that intermingles with groundwater in each sample (Vera *et al*., 2021):

$$\chi = \frac{\delta^{18}O_{gw} - \delta^{18}O_{sw}}{\delta^{18}O_{rw} - \delta^{18}O_{sw}} \quad (2)$$

Where, $d^{18}O_{gw}$, $d^{18}O_{sw}$, $d^{18}O_{rw}$ are $d^{18}O$ value in groundwater, seawater and rain water samples (‰) respectively, and χ is the fraction or percentage of seawater component. The hydrochemistry of saline water and groundwater in coastal aquifers is closely interconnected, largely due to the processes of ion exchange that occur within these systems (Amiri *et al*, 2016). Other indicators used to study the characteristics of groundwater included graphical correlation such as chloride to bicarbonate ratio (Cl/HCO_3) vs Cl (Hajji *et al*., 2022), Cl vs EC (Panno *et al*., 2006), and $d^{18}O$ vs Cl (Geyh and Sofner, 1989).

RESULTS AND DISCUSSION

Stable isotope characteristics

The results of isotope analysis were reported in Table 1, while the correlation between $d^{18}O$ and $d^{2}H$ data was shown in Fig. 3. The graphic served to delineate the different processes that can significantly

Table 1: Stable isotope composition of water samples

No.	Sample code	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
1	C-1	-5.47 ± 0.49	-37 ± 1.47
2	C-2	-6.66 ± 0.40	-45.2 ± 1.2
3	C-3	-6.43 ± 0.28	-41.1 ± 1.4
4	C-4	-6.47 ± 0.41	-41.4 ± 1.3
5	C-5	-3.91 ± 0.68	-28.8 ± 1.8
6	C-6	-6.13 ± 0.24	-40.7 ± 1.0
7	C-7	-6.06 ± 0.44	-40.1 ± 1.3
8	C-8	-5.68 ± 0.75	-38.8 ± 1.7
9	C-9	-6.26 ± 0.37	-41.5 ± 0.8
10	C-10	-7.07 ± 0.45	-50.4 ± 1.3
11	C-11	-6.63 ± 0.39	-40.6 ± 0.8
12	C-12	-7.36 ± 0.44	-44.1 ± 1.1
13	C-13	-7.76 ± 0.37	-45.8 ± 1.3
14	C-14	-8.28 ± 0.32	-52.9 ± 1.8
15	C-15	-7.33 ± 0.40	-46.2 ± 1.1
16	C-16	-8.11 ± 0.33	-51.3 ± 1.3
17	C-17	-7.38 ± 0.30	-50.0 ± 1.5
18	C-18	-7.21 ± 0.37	-51.1 ± 1.1
19	C-19	-7.41 ± 0.43	-46.8 ± 1.2
20	C-20	-7.09 ± 0.38	-51.0 ± 1.1
21	C-21	-7.10 ± 0.61	-48.9 ± 1.3
22	C-22	-6.92 ± 0.38	-47.8 ± 1.1
23	C-23	-7.15 ± 0.51	-51.8 ± 0.9
24	C-24	-7.64 ± 0.14	-45.1 ± 1.7
25	C-25	-6.88 ± 0.56	-50.4 ± 1.1
26	C-26	-6.73 ± 0.38	-51.9 ± 1.5
27	C-27	-7.29 ± 0.28	-46.5 ± 1.1
28	C-28	-8.80 ± 0.11	-55.8 ± 1.0
29	C-29	-8.15 ± 0.15	-49.9 ± 0.9
30	C-30	-8.39 ± 0.56	-50.2 ± 1.1
31	C-31	-7.10 ± 0.59	-43.5 ± 1.6
32	C-32	-7.66 ± 0.35	-48.4 ± 1.1
33	C-33	-7.74 ± 0.52	-43.7 ± 1.5
34	C-34	-5.37 ± 0.50	-43.6 ± 1.2
35	C-35	-7.45 ± 0.21	-47.0 ± 0.2
36	C-36	-6.87 ± 0.56	-42.1 ± 0.9
37	C-37	-7.53 ± 0.49	-47.7 ± 0.7
38	C-38	-7.41 ± 0.08	-52.8 ± 1.4
39	C-39	-6.70 ± 0.40	-40.5 ± 1.3
40	C-40	-6.39 ± 0.28	-50.7 ± 1.2
41	C-41	-5.77 ± 0.46	-45.3 ± 1.2
42	C-42	-7.52 ± 0.20	-42.7 ± 1.7
43	C-43	-8.41 ± 0.08	-52.0 ± 1.4
44	C-44	-7.90 ± 0.61	-48.9 ± 1.3
45	Cirebon seawater 1	-0.73 ± 0.11	-6.8 ± 1.8
46	Cirebon seawater 2	-0.70 ± 0.25	-7.6 ± 2.0
47	Java Seawater	-0.84 ± 0.35	-3.6 ± 1.6

affect the properties of each water sample (Pang *et al*., 2017; Krishan *et al*., 2020).

Upon examination of the sample data points against the meteoric water line, the attributes of groundwater extracted from the Cirebon coastal aquifer can be delineated as follows:

a. Fresh groundwater

Most groundwater samples, consisting of 22 sites or around 50% of total samples in the Cirebon coastal

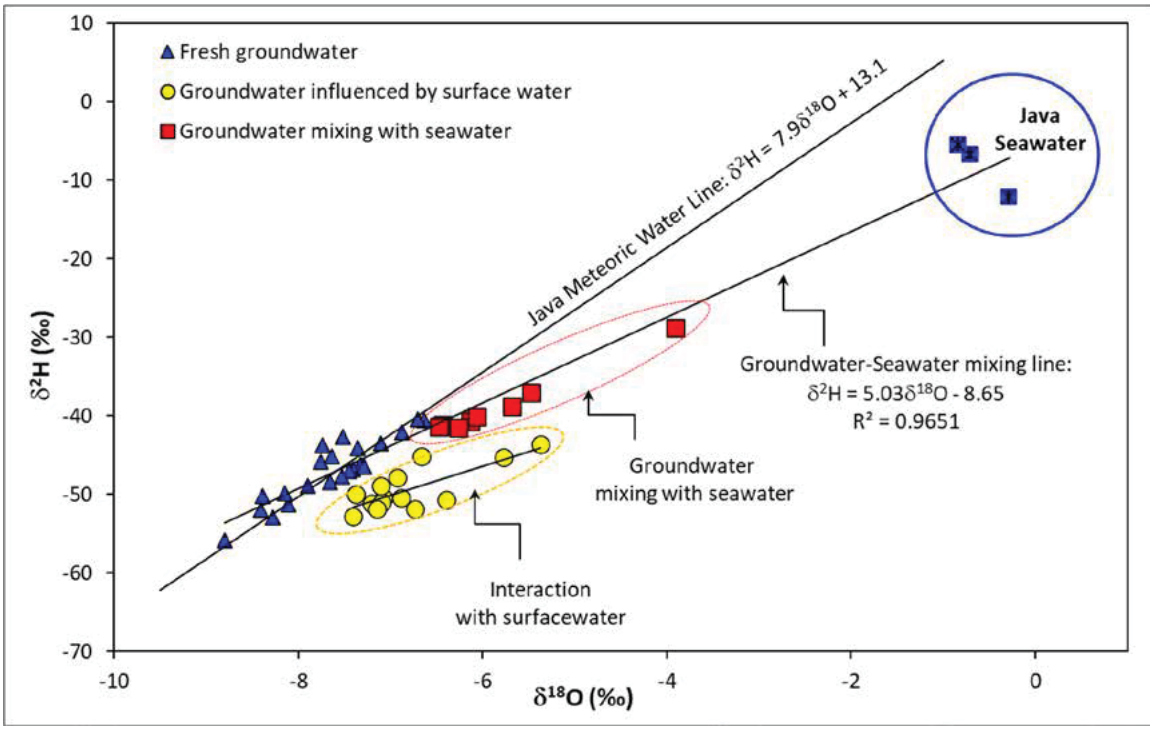


Fig. 3: Plot of δ^2H vs $\delta^{18}O$ of samples in comparison with Java meteoric water line (Sidauruk *et al.,* 2024).

aquifer still retain meteoric water characteristics. The aquifer is underlined more than 1 km from the coastline and is located in the southern part area, which features a hilly landscape.

b. Groundwater – surface water interaction

A total of 14 samples (around 32% of 44 total samples) were plotted similarly to the evaporation line (Horita, 2005). Given that there was no evaporation occurring in the saturated zone, it is plausible that this trend resulted from the interaction between groundwater and surface water, or from the infiltration of water from other sources (Oteng *et al*., 2014). One of the probable mechanisms of this interaction is recharge by runoff (Prada *et al*, 2016), since the study area is located in relatively flat area in the foot of Mount Ciremai. In addition, some of these wells are located near pond and water channel (e.g. C-20, C-23, C-40 and C-41) that might allowed water infiltrating into aquifer (Deng and Bailey, 2022).

c. Groundwater-seawater mixing

A total of 8 (18%) of the 44 samples passed through the salinization process due to seawater intrusion. These sites were positioned at an approximate distance of 1 km from the coastline. The application of Eq. 1 involved the seawater composition detailed in Table 1 as the seawater end member, with the intersection point between the mixing line and the meteoric line illustrated in Fig. 3 representing the rainwater end member, which is -7.55‰. The result of the mixing fraction calculation was presented in Table 2, which indicated that a mixture of about 17.3% – 54.9% of seawater portion has mixed with shallow groundwater in the Cirebon coastal aquifer.

Hydrochemistry characteristics

The results of anion and cation concentrations in shallow groundwater are illustrated in Table 3. An ionic balance of under 5% was observed, reflecting a commendable level of precision in the hydrochemical analysis. The pH measurement for all samples was found to be in the range of 6.84 – 8.24, with an average value of 7.64. A significant number of samples recorded pH values greater than 7, which may be a result of the substantial presence of dissolved sodium

Table 2: Fraction of seawater in contaminated shallow groundwater

No.	Sample code	Seawater fraction (%)	Distance to coastline (m)
1	C-1	32.0	285
2	C-3	17.9	520
3	C-4	17.3	330
4	C-5	54.9	1000
5	C-6	22.3	800
6	C-7	23,3	670
7	C-8	28.9	410
8	C-9	20.4	290

(Na) in the groundwater. However, these values were still within the pH natural level for groundwater (WHO, 2011). Electrical conductivity (EC) values, which indicates Total Dissolved Solids (TDS), for the sites at the distance of 0 – 1000 m away from the coastline range from 0.41 to 12.35 milisiemens per centimeter (mS/cm), with an average of 1.77 mS/cm. The values gradually decreased to 0.45 – 1.59 mS/cm for the sites at a further distance of 1000 m from the coastline. In lower elevation zones and coastal areas, there was a notable increase in electrical conductivity (EC) values in groundwater, primarily resulting from the pronounced salinization of seawater within the groundwater system.

The hydrochemical composition of fresh groundwater was dominated by HCO_3, which was about 35% and was a characteristic of fresh groundwater. However, at some locations, the concentration of Na was relatively higher than that of calcium (Ca) or magnesium (Mg). Fig, 4 provides a box plot diagram that represents the distribution of each chemical component within the various groups. The fresh groundwater and groundwater-surface water interaction groups were relatively similar in their chemical composition and distribution, with differences in isotope composition differentiate as presented in Fig. 3. Conversely, the samples that included mixed seawater displayed a greater degree of dispersion than the preceding groups, especially regarding the composition of Na and Cl, which indicates varying mixing ratios..

A piper diagram, depicted in Fig. 5, was utilized to visually represent the hydrochemical characteristics of groundwater. The diagram was employed to delineate distinct hydrochemical facies or groundwater origins by mapping the levels of cations and significant anions. This representation highlights the sources of dissolved salts and the processes that shape the characteristics of these natural water bodies (Reyes-Toscano *et al.*, 2020). The Piper diagram in Fig. 5 showed that at the cation corner, 26 samples (59%) were spread in Na dominant type, one sample had calcium (Ca) type (2%), six samples had Mg type (14%) and eleven samples had Na-K type. At the anion corner, HCO_3 type predominated in 36 samples (82%), Cl type predominated in 7 samples (16%) and only one sample (2%) had no dominant type. Piper diagram also classified the shallow groundwater into three sub-groups of calcium-bicarbonate (Ca-HCO_3) type. This groundwater represents a standard characteristic of shallow freshwater systems, where the ionic composition is largely attributed to the dissolution of minerals such as calcite. Out of the 44 groundwater samples taken in the study area, the 3 water types identified included 31 samples (70%) that have Ca-HCO_3 water type, i.e., fresh groundwater, where 18 samples located at more than 1.5 km from the coastline, 6 samples at a 1000 – 1500 m, 6 samples at a 500 – 1000 m, and 1 sample at a 0 – 500 m from the coastline. Secondly, 5 samples (11%) have calcium-sodium-bicarbonate (Ca-Na-HCO_3) water type, namely C13, C17, C24, C31, and C35 with the composition of Na is more than 50%, more dominant than Cl. While some samples (C13, C17, C24) are found within 1500 m of the coastline, the water types represented by these samples do not derive from the mixing of freshwater with seawater. This assertion is evidenced by their low chloride levels and depleted isotopic signatures. The shifting from freshwater Ca-HCO_3 type into Ca-Na-HCO_3 type may indicate Na and Ca dissolution process from minerals such as feldspar, as shown in Eq. 3 and Eq. 4 (Shi *et al.*, 2018):

$$2NaAlSi_3O_8 + 2CO_2 + 3\,H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2Na^+ + 2HCO^- \quad (3)$$

Table 3: Chemical composition of water samples in milligram per liter (mg/L)

No.	Code	EC (mS/cm)	pH	Na	K	Ca	Mg	Cl	SO_4	HCO_3
1	C-1	3.69	7.29	716.6	177.5	138.6	129.9	1283.6	181.0	642.8
2	C-2	0.41	8.23	15.6	40.4	15.0	22.6	37.7	27.1	180.7
3	C-3	1.04	7.57	92.1	60.4	26.5	31.1	163.7	28.9	205.2
4	C-4	1.64	7.53	262.5	23.0	30.6	26.7	353.7	4.3	405.8
5	C-5	12.35	6.84	4963.0	162.1	80.7	76.0	6980.9	8.8	698.5
6	C-6	0.87	8.24	135.2	4.8	24.5	20.8	162.9	36.1	275.9
7	C-7	0.95	7.58	156.3	69.4	54.4	78.0	300.4	26.9	428.5
8	C-8	0.90	7.71	80.2	13.6	32.0	37.6	172.1	33.8	225.4
9	C-9	2.29	7.68	368.9	45.0	37.6	43.8	505.0	67.0	571.8
10	C-10	0.71	7.55	44.9	27.5	15.4	41.9	49.4	59.5	269.2
11	C-11	0.62	7.90	75.3	23.1	20.5	47.2	15.3	23.7	429.5
12	C-12	0.86	7.54	80.6	28.4	42.1	18.3	95.3	51.8	290.8
13	C-13	0.48	7.55	89.7	11.5	32.6	16.5	85.4	35.1	222.6
14	C-14	0.53	7.68	38.0	32.2	45.3	12.2	28.9	28.3	252.9
15	C-15	0.62	7.65	71.1	11.6	37.6	19.8	54.7	20.9	342.2
16	C-16	0.65	7.77	53.8	30.4	42.2	12.3	29.4	35.4	301.7
17	C-17	0.81	7.70	101.4	36.4	25.9	27.5	74.0	28.9	375.2
18	C-18	0.88	7.49	40.0	19.7	106.0	33.2	92.5	29.4	371.0
19	C-19	0.48	7.71	29.5	32.3	53.9	18.1	36.7	39.8	242.2
20	C-20	0.49	7.48	27.1	17.8	43.4	37.0	69.7	30.4	228.3
21	C-21	0.48	7.78	33.4	2.5	31.4	27.1	52.8	34.0	213.3
22	C-22	0.45	7.85	57.5	16.0	21.8	31.6	67.6	25.5	225.4
23	C-23	0.67	7.48	18.9	32.1	39.5	48.0	29.2	27.5	407.3
24	C-24	0.89	7.60	110.2	49.3	36.2	22.0	87.4	64.7	402.3
25	C-25	0.86	7.26	82.1	40.5	39.8	32.2	43.7	20.6	507.4
26	C-26	0.98	7.64	95.7	37.9	51.6	66.2	106.6	20.4	520.3
27	C-27	0.52	7.63	56.0	20.2	32.9	15.2	27.1	33.4	288.1
28	C-28	0.57	7.24	73.0	16.4	42.4	41.0	97.1	35.7	289.4
29	C-29	0.67	7.67	38.5	39.9	28.4	34.5	34.7	45.3	334.7
30	C-30	0.63	7.74	40.1	12.7	37.3	32.3	40.0	33.9	278.2
31	C-31	0.95	7.63	170.3	20.6	11.6	67.8	115.5	35.5	542.8
32	C-32	0.94	7.68	90.0	13.0	17.1	64.7	55.2	142.5	404.1
33	C-33	0.87	7.80	95.9	8.1	13.2	78.3	46.5	33.5	551.3
34	C-34	1.03	7.63	117.3	10.1	66.3	64.0	90.3	29.9	584.2
35	C-35	1.01	7.95	123.0	20.5	44.9	31.7	53.5	52.6	504.7
36	C-36	0.56	7.70	50.3	17.4	43.9	46.2	71.2	75.1	261.4
37	C-37	0.91	7.58	53.4	24.5	49.5	36.9	66.1	49.2	357.0
38	C-38	0.58	7.45	39.3	19.1	36.0	25.0	36.5	58.3	192.0
39	C-39	0.61	7.70	30.8	27.4	37.7	45.0	34.5	22.0	354.2
40	C-40	0.89	7.56	83.7	35.7	65.8	60.9	97.6	45.4	489.3
41	C-41	0.69	7.65	53.9	40.7	44.0	50.0	63.0	45.5	371.1
42	C-42	1.59	7.78	171.5	37.8	37.6	76.2	113.9	74.1	797.7
43	C-43	0.55	7.62	61.7	23.1	40.4	31.5	59.6	36.6	300.8
44	C-44	0.80	7.73	71.3	14.5	43.2	43.3	66.2	26.4	466.0

$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO^- \quad (4)$$

The two samples (5%) have calcium-magnesium-chloride (Ca-Mg-Cl) mixed water type with less than 1 km from the coastline, namely C7 and C8 with more than 50% Cl compared to Na, indicating a salinization process through the mixing between groundwater

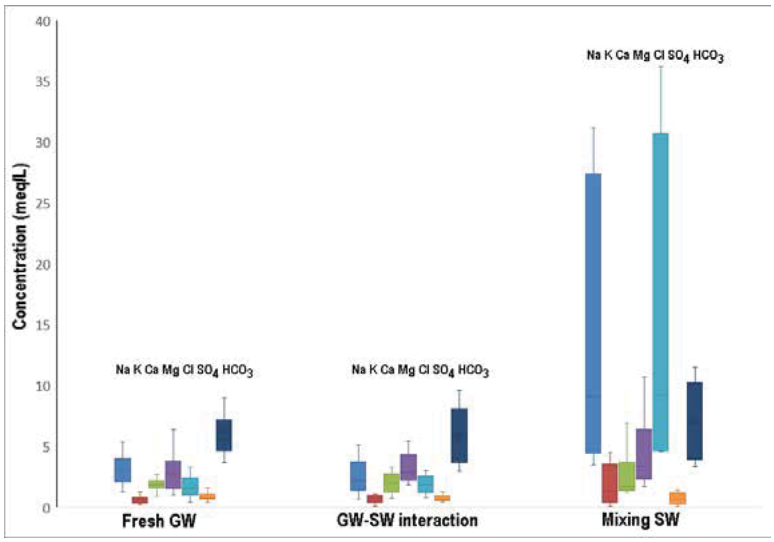


Fig. 4: Boxplot of chemical composition in: fresh groundwater, groundwater – surface water interaction, and groundwater-seawater mixing in Cirebon City

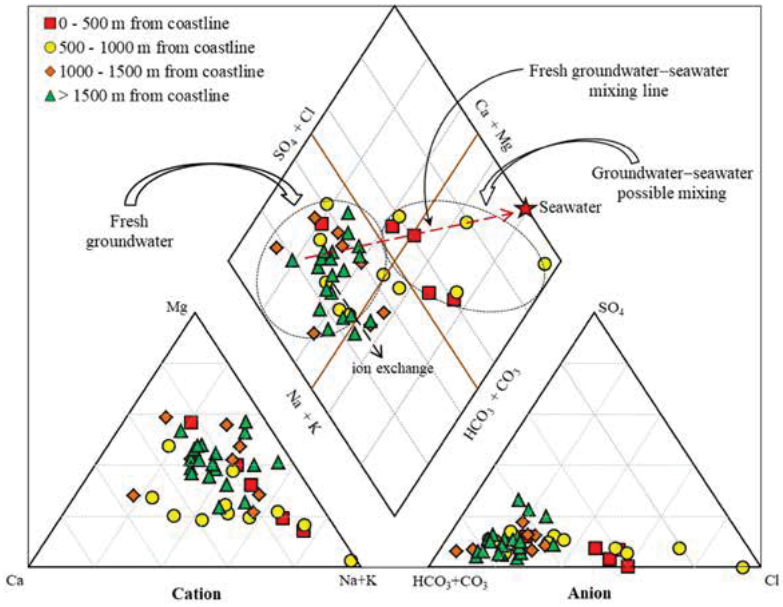


Fig. 5: Piper diagram of shallow groundwater in Cirebon City

and seawater (NaCl), leading to the Ca-Mg-Cl water type. Furthermore, there were 6 samples (14%) of NaCl water type, which indicated a strong seawater influence (Alfarrah and Walraevens, 2018) and were less than 1 km from the coastline.

Fig. 6a shows a molar ratio plot of Cl/HCO_3 vs Cl, indicating that the shallow groundwater in the Cirebon coastal aquifer was classified into three different characteristics. These included Cl/HCO_3 ratio < 0.5 for unaffected or fresh groundwater. The second group was Cl/HCO_3 ratio 0.5 – 6.6 for slightly and moderately affected groundwater, followed by Cl/HCO_3 ratio > 6.6 for strongly affected by seawater intrusion (Al Farrah *et al.*, 2011; Chidambaram *et*

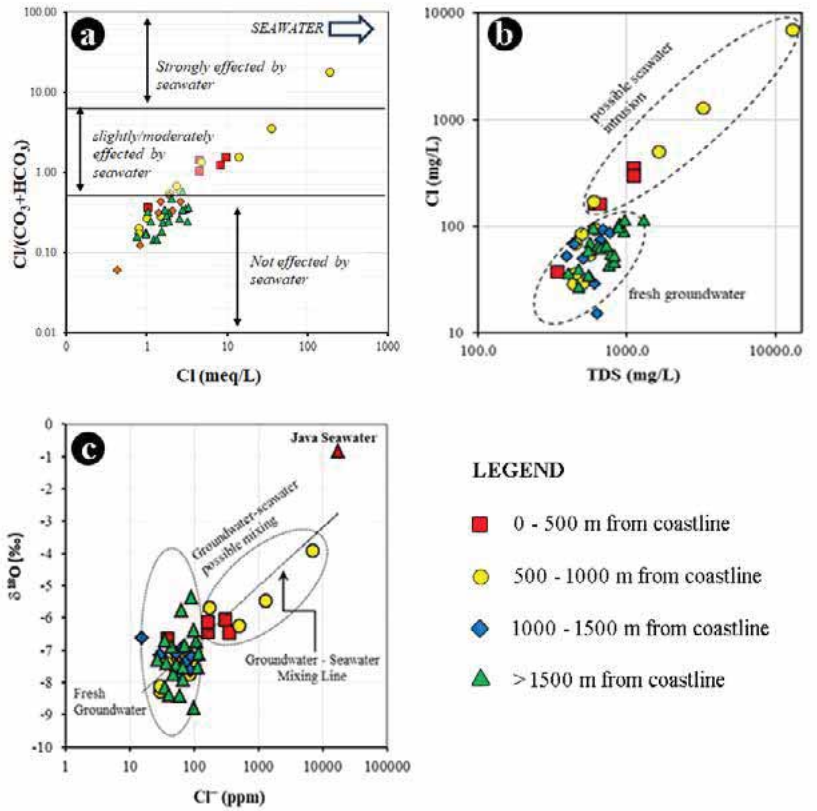


Fig. 6: Plot of (a) Cl/HCO_3 vs Cl, (b) Cl vs TDS, (c) $\delta^{18}O$ vs Cl of shallow groundwater samples in Cirebon City

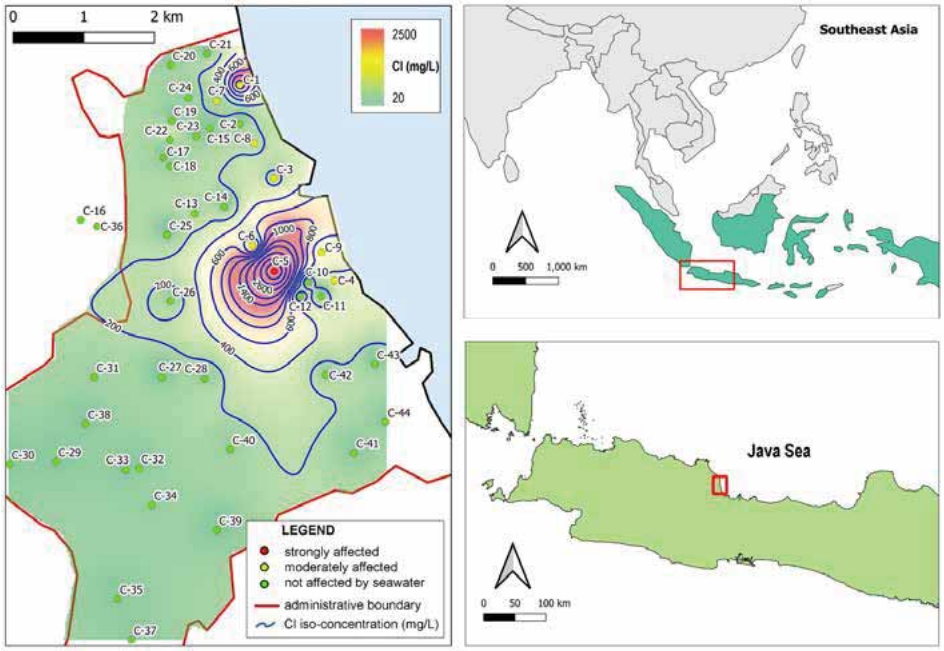


Fig. 7: Chloride distribution in shallow groundwater in Cirebon City

al., 2018). Most shallow groundwater samples were in the first group, while the second group consisted of 7 samples, namely C1, C3, C4, C6, C7, C8, and C9 located approximately 0 – 1000 m distance from the coastline. The third group had one sample, namely, C5 which was located 600 m from the coastline and was the nearest site to the estuary, a highly intruded site by seawater. In terms of hydrogeology, the principal aquifer layer at C5 is formed by alluvial materials, including sand and porous gravel, which have an estimated thickness of around 5 m. Due to its position in the city center, the substantial demand for groundwater has caused a reduction in the water table, potentially leading to greater intrusion of seawater (Jeen *et al.*, 2021). The plotting of Cl vs EC in Fig. 6b and $d^{18}O$ vs Cl in Fig. 6c showed two characteristics of the shallow groundwater, namely fresh groundwater comprising most groundwater samples and groundwater intruded by seawater, consisting of C1, C3, C4, C5, C6, C7, C8 and C9. Consequently, 82% of the shallow groundwater in the study area predominantly exhibited characteristics of fresh groundwater. In contrast, the remaining 8 samples, which constitute 18%, were situated within a distance of 0-1000 meters from the coastline and may have been affected by seawater

As depicted in Fig. 7, the spatial distribution of chloride in shallow groundwater samples reveals that seawater intrusion is notably more intense at the central region of Cirebon City's coastline, particularly in proximity to the C-5 well. In this area, the seawater intrusion spread inland for about 1.5 km from the coastline. Simultaneously, on the northern coastline, the penetration reached an inland distance of about 400 m. The coastline on the southern side of Cirebon has remained largely impervious to seawater intrusion, attributed to its classification as a residential zone. Conversely, the regions close to the coastline and the urban center are allocated for activities related to maritime industries, commerce, and public service functions. Although the World Health Organization (WHO) does not set the health-based limit of Na and Cl concentration in drinking water (WHO, 2011), it is important for local government to address this issue for environmental concern, not only by enforcing stricter regulation for groundwater abstraction, but also from technological intervention such as groundwater artificial recharge (Hussain *et al*., 2019; Verma *et al*., 2019).

CONCLUSION

Based on the analysis results of ^{18}O and ^{2}H stable isotopes, the characteristics of the shallow groundwater from the Cirebon coastal aquifer were classified into three groups. Fresh groundwater constituted the largest share, representing 50% of the total groundwater assessed. Meanwhile, 32% demonstrated interactions with surface water, and the remaining 18% was characterized by seawater intrusion. The shallow groundwater that contaminated by seawater was found within 1.5 km distance from the coastline, in contrast to fresh groundwater, which was predominantly found at greater distances inland. The composition of seawater in shallow groundwater in the study area was estimated around 16.1% – 54.2%. The hydrochemistry of fresh and evaporated groundwater was dominated by HCO_3, with a proportion of 35% and 34%, respectively. Simultaneously, the groundwater influenced by seawater was characterized by a high concentration of sodium ions (41.4%) and chloride ions (39.3%), indicating the phenomenon of salinization. The piper diagram classified the shallow groundwater into 3 types, namely (1) Ca-HCO_3 type, accounting for 31 samples of groundwater (70%), most of which were more than 1.5 km from the coastline. (2) The mixed water type (Ca-Na-HCO_3), consisting of 5 samples of groundwater (11%) which were found beyond 500 m from the shoreline. Meanwhile, in a mixed water type (Ca-Mg-Cl), there are 2 samples of groundwater (5%) with Cl ion composition more dominant than other ions, indicating salinization, located within 1.5 km from the coastline. (3) Lastly, Na-Cl water type, which consisted of 6 samples of groundwater (14%). Located within 1.5 kilometers of the coastline, this shallow groundwater was heavily affected by seawater intrusion, resulting in its inadequate quality for consumption. The disparity in the distance from the coastline associated with seawater contamination prompts an inquiry into whether this occurrence is naturally driven, specifically by lithological factors, or if it is a consequence of anthropogenic activities, particularly the over-extraction of groundwater. In this study, this question is still unanswered due to the lack of lithological data and groundwater extraction data. The chemical techniques implemented in this study facilitate a prompt analysis of the chemical profiles of shallow groundwater and serve as indicators of potential seawater contamination. In the other hand, isotope technique can give unseen

information by chemical data, i.e. surface water infiltration into shallow groundwater. This finding is important because surface water is more vulnerable to anthropogenic contamination, thus also elevating the risk of groundwater anthropogenic contamination. The significant infiltration of seawater into shallow aquifers is a pressing concern that requires urgent attention through evidence-based strategies. It is essential to conduct additional chemical analyses, including examinations for heavy and trace metals, in order to determine the possible health effects on the local community. Further investigation is required to address the insufficient hydrogeological data present in the area. It is important for all stake holders led local government to address this issue, i.e., to limit the abstraction shallow groundwater by increasing the capacity of water piping service owned by the government; to slow or to stop the propagation of seawater intrusion by introducing the artificial groundwater recharge.

AUTHOR CONTRIBUTIONS

S. Satrio contributed in the conceptualization, methodology, original draft preparation and initial writing. R. Prasetio performed data visualization, map generation, writing finalization, editing. E.R. Pujiindiyati supervized chemical analysis and data processing. M.F. Ramadhani supervized field works and in-situ measurement. P. Sidauruk contributed in data interpretation and writing finalization.

ACKNOWLEDGEMENT

The authors are grateful to the field team for their efforts in sample collections and to all Hydrology-Geothermal laboratory staff in Research Organization for Nuclear Energy, National Research and Innovation Agency (BRIN) for their assistance in sample analysis. This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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

©2024 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)
δ	Delta value
‰	Permil (part per thousand)
^{16}O	Oxygen-16 isotope
^{18}O	Oxygen-18 isotope
^{1}H	Hydrogen-1 isotope
^{2}H	Hydrogen-2 isotope
Ca	Calcium
Ca-Mg-Cl	Calcium-magnesium-chloride type
Ca-Na-HCO_3	Calcium-sodium-bicarbonate type
Cl	Chloride
Cl/HCO_3	Chloride to bicarbonate ratio
EC	Electrical conductivity
HCO_3	Bicarbonate
HNO_3	Nitric acid
i.e.	That is
K	Potassium
km	Kilometer
LWIA-LGR	Liquid water isotope analyzer - Los gatos research
m	meter
m	Meter

meq/L	Milliequivalent per liter
Mg	Magnesium
mL	Mililiter
mm	Milimeter
mS/cm	MiliSiemens per centimeter
Na	Natrium (sodium)
pa	Pro analysis
Qa	Sedimentary alluvial deposits
Qac	Coastal sediments
Qpg	Gintung Formation
SO_4	Sulfate
TDS	Total dissolved solids
VSMOW	Vienna standard mean oceanic water
WHO	World Health Organization
χ	Fraction of seawater

REFERENCES

Aksever, F.; Davraz, A., (2018). Determination of stable isotope characteristics and natural radioactivity in drinking waters in Sandıklı basin (Afyonkarahisar-Turkey). Pamukkale Uni. J. Eng. Sci., 24: 545–553 **(9 pages).**

Alfarrah, N.; Walraevens, K., (2018). Groundwater overexploitation and seawater intrusion in coastal areas of arid and semi-arid regions. Water. 10: 143 (**7 pages)**.

Amiri, V.; Nakhaei, M.; Lak, R.; Kholghi, M., (2016). Investigating the salinization and freshening processes of coastal groundwater resources in Urmia aquifer, NW Iran. Environ. Monit. Assess., 188: 233 **(23 pages).**

Bramanto, B.; Gumilar, I.; Sidiq, T.P.; Rahmawan, Y.A.; Abidin, H.Z., (2023). Geodetic evidence of land subsidence in Cirebon, Indonesia. Remote Sens. Appl.: Soc. Environ., 30: 100933 **(14 pages).**

Chidambaram, S.; Sarathidasan, J.; Srinivasamoorthy, K.; Thivya, C.; Thilagavathi, R.; Prasana, M.V.; Singaraja, C.; Nepolian, M., (2018). Assessment of hydrogeochemical status of groundwater in a coastal region of southeast coast of India. Appl. Water Sci., 8: 27: 1–14 **(14 pages).**

Deng, C.; Bailey, R.T., (2022). Assessing the impact of artificial recharge ponds on hydrological fluxes in an irrigated stream–aquifer system. Hydrol., 9:5: 1–17 **(17 pages).**

Ersoy, A.F.; Turan, N.A.; Arslan, H.; Kuleyin, A., (2021). Assessment of seawater intrusion in Kızılırmak delta coastal area (North Turkey) using hydrochemical and isotopic data. Environ. Earth Sci., 80: 400 **(15 pages).**

Ezquerro, L.; Luzón, A.; Simón, J.L.; Liesa, C.L., (2019). Alluvial sedimentation and tectono- stratigraphic evolution in a narrow extensional zigzag basin margin (Northern Teruel Basin, Spain). J. Palaeogeogr., 8: 29 **(25 pages).**

Fasa, A.S.; Revayanti, I.; Wijaya, B., (2022). Analisis ketersediaan dan kebutuhan air bersih domestik di Kabupaten Cirebon. Geoplanart. 4: 2: 104 – 115 **(12 pages).**

Gassama, N.; Dia, A.; Violette, S., (2011). Origin of salinity in a multilayered aquifer with high salinization vulnerability. Hydrol. Process. 26: 168–88 **(21 pages).**

Geyh, M.A.; Sofner, B., (1989). Groundwater analysis of environmental carbon and other isotopes from the Jakarta Basin aquifer, Indonesia. Radiocarbon. 31: 919–925 **(7 pages).**

Gourcy, L.L.; Groening, M.; Aggarwal, P.K., (2005). Stable oxygen and hydrogen isotopes in precipitation. In: Aggarwal, P.K.; Gat, J.R.; Froehlich, K.F. (eds). Isotopes in the water cycle. Springer. 39 – 51 **(13 pages)**.

Hajji, S., Allouche, N., Bouri, S., Aljuaid, A.M., and Hachicha, W., 2022, Assessment of seawater intrusion in coastal aquifers using multivariate statistical analyses and hydrochemical facies evolution-based model. Int. J. Environ. Res. Public Health. 19: 155 **(18 pages).**

Hidayat, S.; Mulyana, H.; Moechtar, H.; Subiyanto, S., (2009). Sedimentologi dan stratigrafi aluvium bawah permukaan di pesisir Cirebon dan sekitarnya. J. Geologi dan Sumberdaya Mineral. 19: 251–260 **(10 pages).**

Horita, J., (2005). Saline waters. In: Aggarwal, P.K.; Gat, J.R.; Froehlich, K.F.O. (eds.). Isotopes in the water cycle: Past, present and future of a developing science. Springer. 271–287 **(17 pages).**

Hussain, M.S.; Abd-Elhamid, H.F.; Javadi, A.A.; Sherif, M.M., (2019). Management of seawater intrusion in coastal aquifers: A review. Water. 11:12 **(20 pages).**

Jeen, S.W.; Kang, J.; Jung, H.; Lee, J., (2021). Review of seawater intrusion in western coastal regions of South Korea. Water. 13: 761 **(27 pages).**

Krishan, G.; Prasad, G.; Kumar, C.P.; Patidar, N.; Yadav, B.K.; Kansal, M.L.; Singh, S.; Sharma, L.M.; Bradley, A.; Verma, S.K., (2020). Identifying the seasonal variability in source of groundwater salinization using deuterium excess- a case study from Mewat, Haryana, India. J. Hydrol.: Reg. Stud., 31: 100724 **(15 pages).**

Liu, F.; Wang, S.; Wang, L.; Shi, L.; Song, X.; Yeh, T.J.; Zhen, P., (2019). Coupling hydrochemistry and stable isotopes to identify the major factors affecting groundwater geochemical evolution in the Heilongdong Spring Basin, North China. J. Geochem. Explor., 205: 106352 **(13 pages**).

Lu, C.; Werner, A.D., (2013). Timescales of seawater intrusion and retreat. Adv. Water Res., 59: 39–51 **(13 pages).**

Mas-Pla, J.; Rodriguez-Florit, A.; Zamorano, M.; Roque, C.; Mencio, A.; Brusi, D., (2012). Anticipating the effects of groundwater withdrawal on seawater intrusion and soil settlement in urban coastal areas. Hydrol. Process, 27, 16: 2352–2366 **(15 pages).**

Pang, Z.; Kong, Y.; Li, J.; Tian, J., (2017). An isotopic geoindicator in the hydrological cycle. Procedia Earth Planet. Sci., 17: 534–537 **(4 pages).**

Panno, S.V.; Hackley, K.C.; Hwang, H.H.; Greenberg, S.E.; Krapac, I.G.; Landsberger, S.; Kelly, D.J.O., (2006). Characterization and identification of Na-Cl sources in groundwater. Groundwater, 44: 176–187 **(12 pages).**

Prada, S.; Cruz, J.V.; Figueira, C., (2016). Using stable isotopes to characterize groundwater recharge sources in the volcanic island of Madeira, Portugal. J. Hydrol., 536: 409–425 **(17 pages).**

Pratama, R.Y.; Sulaksana, N.; Sukiyah, E.; Iskandarsyah, T.Y.W.M.; Novico, F.; Zulfahmi, Z.; Sudjono, E.H.; Ranawijaya, D., (2023). Short-term coastal landscape evolution in Cirebon Bay using coastline environment analysis. J. Environ. Eng. Landscape Manage., 31: 3: 186 – 195 **(10 pages).**

Reyes-Toscano, C.A.; Alfaro-Cuevas-Villanueva, R.; Cortés-Martínez, R.; Morton-Bermea, O.; Hernández-Álvarez, E.; Buenrostro-Delgado, O.; Ávila-Olivera, J.A., (2020). Hydrogeochemical characteristics and assessment of drinking water quality in the urban area of Zamora, Mexico. Water, 12: 556 **(26 pages).**

Rositasari, R.; Setiawan, W.B.; Supriadi, I.H.; Hasanuddin; Prayuda, B., (2011). Coastal vulnerability prediction to climate change: Study case in Cirebon coastal land. J. Ilmu dan Teknologi Kelautan Tropis, 3: 1: 52–64 **(13 pages).**

Sanchez, E.R.S.; Hoyos, S.E.G.; Esteller, M.V.; Morales, M.M.; Astudillo, A.O., (2017). Hydrogeochemistry and water-rock interactions in the urban area of Puebla Valley aquifer (Mexico). J. Geochem. Explor., 181: 219 – 235 **(17 pages).**

Satrio, S.; Prasetio, R.; Syah Alam, B.Y.C.S.S.; Hadian, M.S.D.; Hendarmawan, H., (2021). Comparison of isotope and hydrochemical characteristics of springs in Sembalun – Rinjani area, East Lombok, West Nusa Tenggara, Indonesia before and after the earthquake events in 2018. Bull. Geol. Soc. Malaysia, 71: 215–226 **(12 pages).**

Shi, X.; Wang, Y.; Jiao, J.J.; Wen, H.; Dong, R., (2018). Assessing major factors affecting shallow groundwater geochemical evolution in a highly urbanized coastal area of Shenzhen City, China. J. Geochem. Expl., 184: 17–27 **(11 pages)**.

Sidibé, A.M.; Lin, X.; Koné, S., (2019). Assessing groundwater mineralization process, quality, and isotopic recharge origin in the Sahel region in Africa. Water. 11: 789 **(19 pages).**

Silitonga, P.H.; Masria, M.; Suwarna, N., (1996). Peta geologi lembar Cirebon, Jawa, skala 1:100.000. Pusat Penelitian dan Pengembangan Geologi, Bandung.

Tweed, S.; Leblanc, M.; Cartwright, I.; Bass, A.M.; Marc, V.; Thao, N.B.; Duc, N.D.; Massuel, S.; Kuar, U.S., (2020). Stable isotopes of water in hydrogeology. In: Maurice, P. (ed), Encyclopedia of Water: Science, Technology, and Society. John Wiley and Sons, Inc., New Jersey (**10 pages)**.

Vasu, D.; Singh, S.K.; Tywary, P.; Sahu, N.; Ray, S.K.; Butte, P.; Duraisimi, V.P., (2017), Influence of geochemical processes on hydrochemistry and irrigation suitability of groundwater in part of semi-arid Deccan Plateau, India. Appl. Water Sci., 13: 3803 – 3815 **(13 pages).**

Vera, A.; Pino-Vargas, E.; Verma, M.P.; Chucuya, S.; Chavarri, E.; Canales, M.; Torres-Martinez, J.A.; Mora, A.; Mahlknecht, J., (2021). Hydrodynamics, hydrochemistry, and stable isotope geochemistry to assess temporal behavior of seawater intrusion in the La Yarada Aquifer in the vicinity of Atacama Desert, Tacna, Peru. Water, 13: 3161 (**15 pages).**

Verma, N.; Anda, M.; Wijayanti, W., (2019). Artificial recharge for sustainable groundwater management plan in Yogyakarta. Indonesian J. Urban Environ. Technol., 2: 2: 120 – 133 **(14 pages).**

WHO, (2011). Guidelines for drinking water quality, fourth edition. Vienna, Austria (**541 pages).**

Wijatna, A.B.; Kayyis, M.; Satrio, S.; Pujiindiyati, E.R., (2019). Study of seawater intrusion in deep aquifers of Semarang coast using natural isotopes and hydrochemicals. Indones. J. Geosci., 6: 1: 17–28 **(12 pages).**

AUTHOR (S) BIOSKETCHES

Satrio, S., Dr., Researcher, Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: *satr002@brin.go.id*
- ORCID: 0000-0002-0233-179X
- Web of Science ResearcherID: NA
- Scopus Author ID: 56622989800
- Homepage: www.brin.go.id

Prasetio, R., Dr., Researcher, Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: *rasi.prasetio@brin.go.id*
- ORCID: 0000-0002-6682-653X
- Web of Science ResearcherID: NA
- Scopus Author ID: 55352219500
- Homepage: www.brin.go.id

Pujiindiyati, E.R.P., B.A., Researcher, Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: *evar001@brin.go.id*
- ORCID: 0009-0004-7625-8339
- Web of Science ResearcherID: NA
- Scopus Author ID: 57202014471
- Homepage: www.brin.go.id

Ramadhani, M.F., B.A., Researcher, Research Center for Radiation Detection and Nuclear Analysis Technology , National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: moch046@brin.go.id
- ORCID: 0000-0002-2565-8912
- Web of Science ResearcherID: NA
- Scopus Author ID: 58480908300
- Homepage: www.brin.go.id

Sidauruk, P., Ph.D., Professor, Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: past001@brin.go.id
- ORCID: 0009-0002-1202-7094
- Web of Science ResearcherID: LIF-1869-2024
- Scopus Author ID: 6507504834
- Homepage: www.brin.go.id

HOW TO CITE THIS ARTICLE

Satrio, S.; Prasetio, R.; Pujiindiyati, E.R.; Ramadhani, .F.; Sidauruk, P., (2024). Characterization of shallow groundwater in coastal aquifer of urbanized area using stable isotope and hydrochemical approaches. Global J. Environ. Sci. Manage., 10(SI): 123-136.

DOI: 10.22034/gjesm.2024.10.SI.08

URL: https://www.gjesm.net/article_716180.html

Global J. Environ. Sci. Manage. 10(SI): 137-152, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH ARTICLE

Environmentally friendly synthesis of nanoporous silica materials using quercetin as a morphogenetic agent

A.R. Zare Hoseinabadi[1], E. Rafiei Taqanaki[1], S. Hafez Ghoran[1], A.M. Amani[1], H. Kamyab[2,3,4,*], A. Razmfarsa[5], E. Khalili[6], M. Yusuf[7,8], S. Rajendran[9]

[1] *Department of Medical Nanotechnology, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran*

[2] *Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia*

[3] *Universidad UTE, Centro de Investigación en Salud Públicay Epidemiología Clínica, Quito 170527, Ecuador*

[4] *Department of Biomaterials, Saveetha Dental College, and Hospital, Saveetha Institute of Medical and Technical Sciences, Chennai, 600 077, India*

[5] *Faculty of Science, Department of Biology and Genetics, Islamic Azad University, Mashhad Branch, Razavi Khorasan, Iran*

[6] *Department of Electrical and Engineering, Faculty of Engineering and Physical Science, Centre of Vision Speech and Processing, University of Surrey, United Kingdom*

[7] *Clean Energy Technologies Research Institute, Process Systems Engineering, Faculty of Engineering and Applied Science, University of Regina, Canada*

[8] *Centre of Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India*

[9] *Instituto de Alta Investigación, Universidad de Tarapacá, Arica 1000000, Chile*

ARTICLE INFO

Article History:
Received 02 May 2024
Revised 27 July 2024
Accepted 02 October 2024

Keywords:
Antioxidant properties
Antiviral assay
Cell viability
Mesoporous silica nanoparticles
Quercetin
Templating technique

ABSTRACT

BACKGROUND AND OBJECTIVES: The synthesis of mesoporous silica nanoparticles using non-surfactant agents is gaining popularity owing to the easier purification and lower toxicity of this method compared to traditional surfactant-based ones. The potential of mesoporous silica nanoparticles as advanced nanocarriers for health-related applications is increasingly recognized. Quercetin, a potent free-radical scavenging antioxidant that relies heavily on the intracellular supply of reduced glutathione, has garnered significant interest in the scientific community. In spite of recent progress, the mechanisms underlying the development of the porous framework have largely gone unexplored. The primary aim of this study is to explore the feasibility of utilizing quercetin as a template for the synthesis of mesoporous silica nanoparticles, circumventing the need for conventional
METHODS: This research investigates the impact of the chemical structure and properties
METHODS: This research investigates the impact of the chemical structure and properties of polyphenols, specifically quercetin, on their templating potential. The study reveals the arrangement of quercetin, which acts as a model for the development of mesoporous silica nanoparticles, forming a supramolecular structure that facilitates silica binding. The composition of this supramolecular framework leads to unconventional and variable pore structures. The scanning electron microscopy, transmission electron microscopy, Fourier-transform infrared spectroscopy, x-ray diffraction analysis, energy-dispersive X-ray spectroscopy, and Brunauer–Emmett–Teller analysis were used to characterize the quercetin-templated mesoporous silica nanoparticles and provide detailed insights into their morphology.
FINDINGS: The results from the viability test and antiviral assays demonstrated that quercetin-templated mesoporous silica nanoparticles are non-toxic and possess inhibitory and antiviral properties that are comparable to those of Oseltamivir, which served as a positive control. Quercetin served as a non-surfactant, neutral template in an ammonia and ethanol mixture, resulting in approximately spherical particles with monodisperse diameters of about 180 nanometers. These nanoparticles of mesoporous silica showed a concentration-dependent efficacy in inhibiting pathogenic microorganisms. In x-ray diffraction pattern for Mesoporous silica nanoparticles, a number of Bragg's reflections referring to the (111), (200), and (220) sets of lattice planes were detected, which can be described by the fundamental face center cubic structure of mesoporous silica nanostructures. Because of the smaller particle diameter impact and incomplete internal structure of the nanostructures, the intense peak at 2θ= 24 degrees demonstrated the silica peak, which reflected crystalline nature. According to calculations based on the Brunauer–Emmett–Teller method, the specific surface area of Quercetin-templated mesoporous silica nanoparticles was determined to be 55.227 cubic meters. Furthermore, the Barrett-Joyner-Halenda analysis provided measurements of the pore size at 24.312 nm and the pore volume at 0.336 square centimeters per gram, respectively.
CONCLUSION: The study results outcomes demonstrated that quercetin forms a macromolecular scaffold that functions as a template for the formation of mesoporous silica nanoparticles. The irregular pore structure observed is attributed to the unique characteristics of quercetin. Using small-angle x-ray scattering, detailed information was obtained regarding the constituents and the porous nature of the resulting mesoporous silica nanoparticles. This study reveals innovative insights into the mechanisms by which the macromolecular structure of the template governs the dimensions of particles and the process of pore formation. The role of quercetin in the morphogenetic development of mesoporous silica nanoparticles has been thoroughly investigated. In addition, quercetin-templated mesoporous silica nanoparticles exhibited significant antioxidant properties, akin to butylated hydroxytoluene, and showed great potential for various clinical applications.

DOI: 10.22034/gjesm.2024.10.SI.09

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

NUMBER OF REFERENCES
40

NUMBER OF FIGURES
9

NUMBER OF TABLES
0

*Corresponding Author:
Email: *hesam_kamyab@yahoo.com*
Phone: +6017 782 0054
ORCID: 0000-0002-5272-2297

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Mesoporous silica nanoparticles (MSNs) are gaining popularity because of their large surface area and tunable pore size, hydrophilicity properties, quick and efficient surface modification, and biocompatibility specifications. These characteristics are highly desirable for a variety of applications, such as medication delivery, catalysis, imaging, and sensing/detecting (Abbasi *et al.,* 2021, Vafa *et al.,* 2021, Vafa *et al.,* 2022). The realization of this promise necessitates the use of monodisperse mesoporous silica nanoparticles (MSNs) measuring between 50 and 200 nanometers (nm) to improve cellular uptake, as well as possessing large mesopores to allow for the encapsulation of biomacromolecules, particularly within the biomedical sector (Gao and Zharov, 2014; Vafa *et al.,* 2023). Natural resources containing silica are more considered because of their low cost, biocompatibility, bioactivity, and bioavailability. Furthermore, for these purposes, the intrinsic capacity generated by interconnected pores will be valuable, and it can be caped using different materials and decapped under special conditions such as the acidic potential of hydrogen (pH). Surfactant templating has become the most popular method for synthesizing MSNs. In 1992, it was discovered that when surfactant molecules self-assemble in the aqueous systems of silica substances, spontaneous silica-surfactant mesophase co-assembly would occur (Kresge *et al.,* 1992). Following the removal of the surfactant, the resultant composition includes relatively standard solids of the mesoporous matrix, as well as the hazardous replication of the supramolecular structures that were self-assembled by the surfactant. A broad range of compositions of mesoporous solids have been developed in recent years (Fröba *et al.,* 1999; Stevens *et al.,* 2006; Zhao *et al.,* 1998), and the ability to tune porous structure dimensions from one to tens of nanometers has been illustrated by leveraging a range of surfactants. Using templating chemicals, typically surfactants, a variety of techniques for mesoporous silica nanoparticles (MSNP) production have been established (Han and Che, 2013). Wei *et al.* (1998) maintained that, decades later, homogenous silica with a mesoporous matrix might well be manufactured by employing D-maltose, D-glucose, and dibenzoyl-L-tartaric acid, resurrecting the application of nonsurfactant substances as templating agents. Other chemicals, including organic hydroxy-carboxylic acids, poly(propylene)imine dendrimers (like lactic acid, tartaric acid, malic acid, and citric acid), complexes of the β-cyclodextrinurea-urea, and sugars (like fructose and sucrose), were found to be effective in generating mesoporous silica monoliths in corresponding tests (Pang *et al.,* 2001a; Pang *et al.,* 2001b; Vafa *et al.,* 2024; Wei *et al.,* 1999; Zheng *et al.,* 2002). Subsequently, the technique was effectively utilized for the synthesis of nanostructures. Although the diameter of nonsurfactant-based templated MSNs may differ without losing monodispersity, owing to the limited scale of the templating species, the pore diameter becomes typically less than 4 nm (Gao and Zharov, 2014). Plants that possess a significant concentration of polyphenols often display complex structural arrangements. In this framework, phenolic rings serve as the essential monomers, which are further classified into phenolic acids and phenolic alcohols (Abbas *et al.,* 2017; Amani *et al.,* 2024). A revolutionary technique for creating mesoporous silica nanostructures with accurate pore volume spatial distribution, high surface area, and adjustable pore diameters is the green template. It has been demonstrated that this template can be completely removed and recycled from silica sustainably by quickly eliminating water. In addition, the porous structure has a high thermal resistance (Luo *et al.,* 2019; Xu *et al.,* 2008). An abundant flavonoid antioxidant agent found in nature is quercetin (QU). The extensive array of functions it exhibits, including the modulation of cell growth and engagement through type II estrogen binding sites, positions it as a highly promising candidate for the advancement of anti-tumor therapies. However, tyrosine kinase inhibition is typically present as a glycoside that, during intestinal absorption, transforms into glucuronide/sulfate conjugates. Furthermore, the circulatory system uses only conjugate derivatives. Previous research has shown that QU can cure metabolic ailments, allergy syndromes, eye issues, arthritis, and heart failure. Moreover, it is a strong antioxidant that protects against tissue deterioration over time brought on by a range of medication toxicities (David *et al.,* 2016; Lakhanpal and Rai, 2007). Some plants containing high levels of polyphenols possess complicated structures. In this respect, the basic monomer is a phenolic ring that is classified into phenolic acids and phenolic alcohols (Abbas *et*

al., 2017; Amani *et al.,* 2024). The green template strategy has emerged as a groundbreaking method for generating mesoporous silica nanostructures, enabling the manipulation of pore diameters, the accurate spatial distribution of pore volume, and the attainment of a significant surface area. It has been shown that by rapidly extracting water, this template can be fully removed and recycled from silica in an environmentally friendly manner. Aside from that, the porous structure is very thermally resistant (Luo *et al.,* 2019; Xu *et al.,* 2008). QU is a flavonoid antioxidant agent abundantly available in nature. A large percentage of its behaviors, including cell growth regulation and interaction through type II estrogen binding sites, make it a potential anti-tumor drug applicant. Nevertheless, tyrosine kinase inhibition is commonly found as a glycoside, which is converted to glucuronide/sulfate conjugates during gut absorption. Moreover, only conjugate derivatives are used in the circulatory system. QU has been demonstrated to reduce the risk of heart failure and cure eye disorders, arthritis, allergic syndromes, and metabolic diseases in previous studies. It is also a potent antioxidant that has been noticed to defend against tissue long-term damage caused by a variety of drug toxicity (David *et al.,* 2016; Lakhanpal and Rai, 2007). The aim of this study is to explore the environmentally friendly synthesis of MSNs using QU as a non-toxic morphogenetic agent. By investigating the templating potential of QU, the research seeks to elucidate the structural characteristics and mechanisms underlying the formation of unique porous frameworks in MSNs. The study centers on the characterization of the resultant nanoparticles, alongside an assessment of their biocompatibility and prospective biomedical applications, particularly in drug delivery and antimicrobial activities. Ultimately, the findings could contribute to the development of safe and effective nanocarriers for health-related purposes, advancing the understanding of polyphenol-assisted synthesis in nanotechnology. This study has been carried out in Iran in 2024.

MATERIALS AND METHODS

Sigma-Aldrich provided tetraethoxysilane (TEOS), concentrated 28 percent % ammonium hydroxide, QU, absolute ethanol, concentrated 30% hydrogen peroxide, and concentrated 98% sulfuric acid. All of these materials were used as acquired.

Silica nanoporous material synthesis

QU was used as a templating agent throughout the production of nanoporous silica particles, and it was dissolved in 150 mL of ethanol before being applied to a mixture of ammonia and water. Following the synthesis process, the particulates were collected through centrifugation and subsequently subjected to thorough washing with water and ethanol prior to their redispersed. The residues of the organic compounds were removed using an acid piranha procedure. To eliminate all of the ethanol, 0.1 gram (g) of particulates were distributed throughout the water multiple times. The resulting aqueous solution was treated for 2 hours (h) at 60 degrees Celsius (°C) using a diluted piranha solution, consisting of 10% hydrogen peroxide (H_2O_2) and 2 molar sulfuric acid (H_2SO_4), while stirring the mixture. The process was completed after centrifuging the suspension for 10 minutes at 7800 Revolutions per minute (rpm). To ensure the removal of acidic substances, the particulates were washed three times with water prior to their re-dispersion in the aqueous solution.

Characterization

Scanning electron microscopy (SEM) was performed using the Hitachi S-4800 equipment. In addition to assessing the silica particle properties, SEM was used to investigate the QU aggregates. SEM was used to determine the median size and distribution of the associated nanostructures. Transmission electron microscopy (TEM) was performed using the JEOL JEM instrument, 2200fs model. Nitrogen adsorbents were employed to assess the surface area and volume of the porous structures present in crystalline silica. At 77 K, nitrogen desorption and adsorption processes were quantified using the micromeritics triflex. The Brunauer-Emmett-Teller (BET) method was also employed to determine the unique surface area. In addition, small angle X-ray scattering (SAXS) analysis methods were used to determine the pore diameter and surface unevenness of the particles. X-ray photoelectron spectroscopy (XPS), which is used to detect empirical atomic properties and chemical composition, was employed in this study to investigate the molecular structure of the chemical configuration and the electronic institution of the components inside the sample. The development of Fourier transform infrared (FTIR) spectroscopy as an experimental analytical method allows for

the differentiation of organic materials from certain inorganic substances through the use of infrared radiation (IR). The X-ray diffraction (XRD) test was used as a non-destructive evaluation method to determine the composition of crystalline phases and structures present in these nanostructures.

Antioxidant assay

The antioxidant ability of QU-synthesized MSNs was determined on the basis of scavenging the free radicals, 2,2-diphenyl-1-picrylhydrazyl ($DPPH^{\bullet}$), using a spectrophotometric assay (Ghoran *et al.,* 2020). The different concentrations of MSNs were employed in the range of 62.5-100 microgram per mL (µg/mL) (Loizzo *et al.,* 2012). Butylated hydroxytoluene (BHT) was used as a positive control. After having incubated for 30 minutes at 37 °C, absorbance at 517 nm was measured. The percentage inhibition of $DPPH^{\bullet}$ radical formation was measured using Eq. (1) (Loizzo *et al.,* 2012):

$$\text{DPPH scavenging effect}(\%) = [(A0 - A1)/A0) \times 100] \quad (1)$$

where A_0 is the absorbance of the control reaction, and A_1 is the absorbance of the presence of all the extract samples and standard.

Antibacterial assay

In this study, two bacterial species were used in the inhibition zone, i.e., minimum bactericidal concentration (MBC) and minimum inhibitory concentration (MIC) tests. *Escherichia coli* (ATCC8739) and *Staphylococcus aureus* (ATCC6538) were used as bacterial strains in the investigation. The medium of lactose broth (LB) and fresh nutrient broth (NB) was given to *E. coli* and *S. aureus*, allowing them to develop for 24 to 48 h in a typical environment with 37 °C temperature. Serial dilution was used to produce different dilutions of each bacterial strain suspension. The amount of absorption was next evaluated by employing a spectrophotometer calibrated to 580 nm. Each bacterial suspension strain employed in previous comparable studies has been adjusted to have 0.5 normal McFarland turbidity.

Growth inhibitory zone determination

The growth inhibitor zone diameter of each sample was measured using a Disc Diffusion Protocol which was established initially in the 1940s and, since that time, has been further refined by the recommendations of the Clinical and Laboratory Standard Institute (CLSI) (Balouiri *et al.,* 2016). The bacterial solutions, *S. aureus* and *E. coli*, were individually grown at a 0.5 McFarland concentration (Mueller-Hinton agar). The discs soaked in various quantities of the sample (QU-templated MSNs) were then put on the culture medium at the appropriate distances. The experiment included a disc with penicillin as the positive control, alongside a chemically inert blank disc designated as the negative control. Following a 24-hour incubation at 37 °C, the diameters of the zones of growth inhibition were measured under suitable conditions. Both experimental procedures were repeated three times.

Minimum bactericidal concentration and minimum inhibitory concentration determination

The MBC and MIC of various nanostructures were determined using the tube dilution method. A tube was supplied separately with 9 mL of Mueller-Hinton Broth, 1 mL of a sample (QU-templated MSNs). The serial dilution method then produced different concentrations of each material. The suspension of the bacterial strain at 0.5 McFarland levels (0.1 mL) was combined in all tubes with the preceding combination. The tubes may be incubated overnight at 37 °C. The MIC was described as the lowest concentration during which the bacterial growth was stopped, without turbidity in tubes. The MBC was found to be the lowest nanomaterial level, producing a decrease of 99.9% of 10^8, 0.5 McFarland's standard (CFU/mL) in bacteria colonies from the original inoculum (Balouiri *et al.,* 2016). In this context, the medium tubes that are free of micro-organisms are designated as the negative controls, whereas the medium tube that includes micro-organisms without a sample is identified as the positive controls. The same technique has been used in conventional medicine for the comparison of antibacterial action with an antibiotic (penicillin). The experiments have been repeated at least three times to ensure reliability.

Cytotoxicity endpoints and cell culture

A cellular study was conducted using fibroblast cells. The fibroblast cell line was acquired from the National Cell Bank of Iran by the Pasteur Institute. The cell lines were produced in a flask of 5% carbon

dioxide (CO_2), 37 °C (Gibco, Scotland) of the RPMI-1640 medium with 10% of fetal bovine serum (FBS, PAA, Austria), and 1% penicillin/streptomycin. The cells were cultured in a flask. When the cells achieved a confluence of about 70–80%, they were washed with phosphate-buffered saline (PBS). The cells were then removed with trypsin/EDTA from the flask for a brief time. The evaluation of cell density was conducted utilizing a Neubauer chamber in conjunction with trypan blue staining of the harvested cells. The cytotoxicity of the produced sample (QU-templated MSNs) has been evaluated in various doses by using the mitochondrial dehydrogenase-dependent 3-4, 5-dimethylthiazolyl-2-2, and 5-diphenyltetrazolium bromide (MTT) assay (Twentyman and Luscombe, 1987). The cells cultured were seeded in 96-well cell cultures at a density of 1×10^5 cells per well. The cells were incubated at 5% CO_2 and 37 °C for 24 h. After the incubation period, the culture media was removed and the cells were incubated at different concentrations in the new medium for 24, 48, and 72 h (5, 10, 20, 50, 100, 150, 200, and 250 g/mL). Cells with no samples were negative controls. A 100 mL MTT dye solution was well received at a concentration of (0.5 mg/mL in PBS), then incubated for 3 h. Then, each cell received 100 mL of DMSO (Merck, Germany). A plate reader was used to evaluate 570 and 650 nm absorption (Perkin Elmer, Boston, USA). The cytotoxicity and viability of the cells were evaluated using the control group, which had 0 percent cytotoxicity volume and 100 percent viability volume. Cytotoxicity and viability percentages were measured for different sample concentrations using Eqs. (2) and (3), respectively (Luo *et al.,* 2019):

$$\text{Cell viability}(\%) = \frac{AbSt570 - AbSt650}{AbCon570 - AbCon650} \times 100 \quad (2)$$

$$\text{Cytotoxicity (\%)} = 1 - \text{cell viability (\%)} \quad (3)$$

where AbSt570 and AbSt650 have sample light absorption values of 570 and 650 nm, respectively, and AbCon570 and AbCon650 represent the light absorption of control samples.

Statistical analysis

All the tests were performed three times, and results were shown as the mean ± standard (SD). To monitor differences between variables, an analysis of variance (ANOVA) was conducted. The data were statistically examined using the Social Sciences Statistics Package (SPSS), version 20.0. (SPSS Inc. USA). For comparison, T-tests were employed. When the *P*-value was below 0.05, it was considered that statistically significant results were obtained ($P < 0.05$). All tests were performed three times.

RESULTS AND DISCUSSION

Amorphous silica is found in a variety of living organisms, including diatoms, silicoflagellates, radiolarians, and sponges (Maldonado *et al.,* 2005; Riesgo *et al.,* 2021). The structural configuration of molecules and atoms in amorphous silica, or non-crystalline silica, is defined by a disordered and chaotic organization, devoid of a regular pattern. Peak broadening was also linked to the formation of porous structures in another analysis. Another characterization analysis, like TEM and BET surface analyzer, can be used to prove this theory. The presence of non-crystalline frameworks owing to pore formation through the QU template is shown by the widening/stretching of the sample diffraction peaks. According to Kioni *et al.,* wide-angle x-ray diffraction exhibits an amorphous-like form, which correlates to the existence of large pores in the material (Kioni *et al.,* 2011). The crystalline structure of QU-templated MSNPs is determined using an X-ray diffraction pattern. The existence of silica nanoparticles can be determined using XRD analysis. The particulates are crystalline in nature, as can be seen in Fig. 1, indicating that silica has a porous composition. The pores formed within silica are responsible for the peak broadening of diffraction peaks in the QU–templated silica. In profile (Fig. 1), diffraction peaks broadened at around 2q= 22–24°, as in the diffraction pattern of the amorphous phase of silica. The sharp peak at 2θ= 24° displays the silica peak, which represents the crystalline nature of the nanostructures, because of the incomplete internal structure and lower particle diameter influence. Bragg's reflections pertaining to the (111), (200), and (220) sets of lattice planes are identified in the XRD pattern for MSNs. These reflections can be explained by the basic face center cubic (FCC) structure of mesoporous silica nanostructures.

A mesoporous silica nanoparticle is a specific kind of mesoporous silica nanostructured material featuring a hollow spherical shape. Fig. 2 shows an

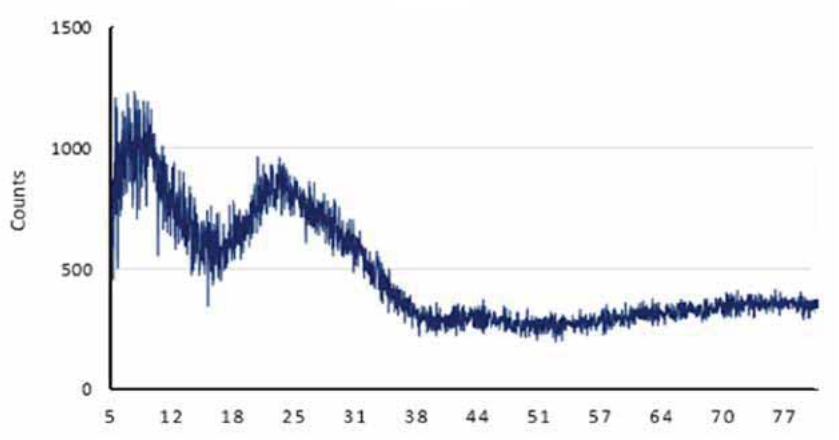


Fig. 1: Powder XRD pattern of synthesized QU-templated MSNPs.

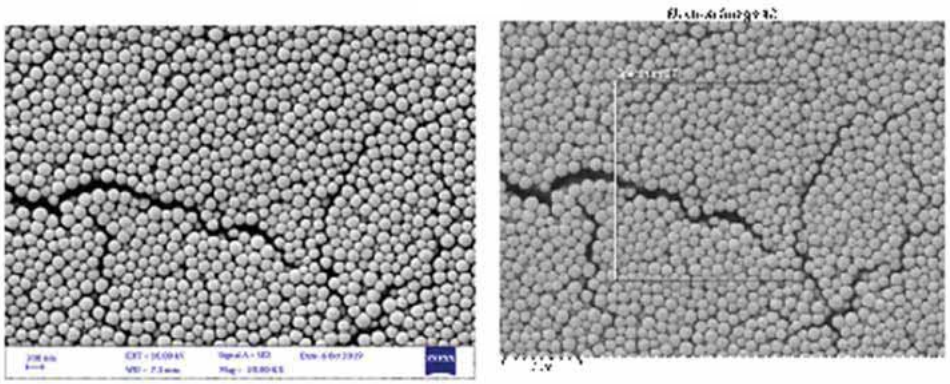


Fig. 2: SEM analysis of the synthesized QU-templated MSNs

SEM representation of QU-templated MSNs. TEOS as the silica precursor and cetyltrimethylammonium bromide (CTAB) as the pore-forming agent were used to produce QU-templated MSNs with a mean diameter of around 180 nm. The solid Stober spheres were effectively transformed into homogeneous hollow spheres when simply treated with sodium carbonate (Na_2CO_3) in the presence of CTAB at a sufficient concentration.

Fig. 3 shows the TEM images of QU-templated MSNs. The traditional SEM image of QU-templated MSNs shows spherical and monodisperse particulates, with a monodisperse particle having an average scale of 100–180 nm. The TEM image clearly shows that the QU-templated MSNs had a porous configuration with well-lined-up porous spherical arrangement and formed excellent nanoclusters. Sarkar *et al.* (2016) created MSN-Folic acid-quercetin as a targeted delivery system for breast cancer cells. The authors estimated the average diameter of MSNs to be 80–120 nm.

With nitrogen sorption measurement techniques, the dried nanostructure specimens were assessed for pore volume (V_p) as well as specific surface area (SSA_{BET}). The specific surface area was measured using the BET principle, and pore volume was calculated using the cumulative adsorbed quantity at a relative pressure of p/p_0 = 0.9 (Matshitse, 2010). Since the porosity variations between silica specimens were already apparent based on the various synthesis parameters, nitrogen sorption observations were taken for all porous silicon nanomaterial samples but only for one silica nano-sized sample. The N_2 adsorption/desorption isotherm models and the

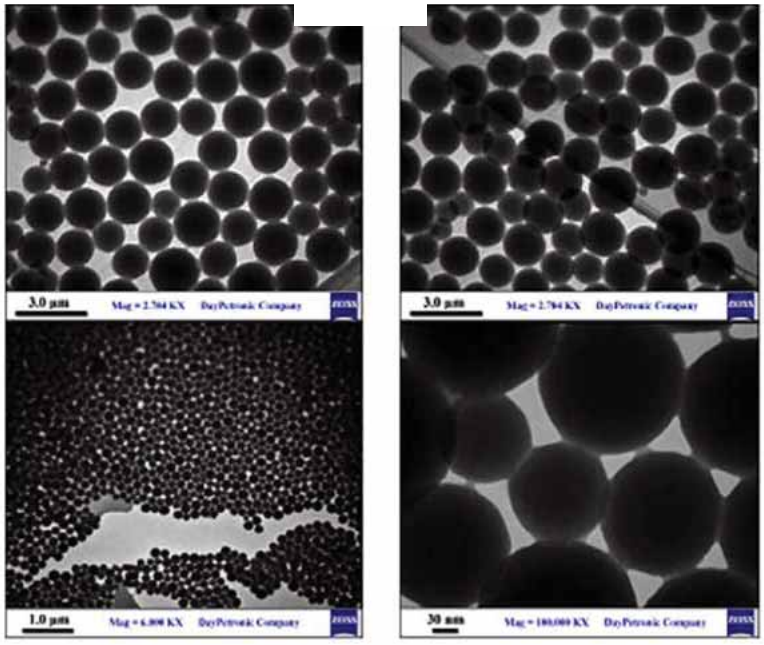


Fig. 3: TEM images of well-shaped monodisperse Quercetin-templated MSNs

pore size distribution of the QU-templated MSNs are seen in Fig. 4. The specific surface area of QU-templated MSNs was 55.227 m^2/g, according to BET surface area calculations, and the measured Barrett-Joyner-Halenda (BJH) pore size and pore volume were 24.312 nm and 0.336 cm^3/g, respectively (Fig. 4). The aminated MSNs provided a smaller surface area than the non-functional MSNs, meaning that the aminopropyl group effectively attached to the surface of the aminated MSNs. Because of the huge pore size and volume, these nanoparticles are predicted to have a special ability to load therapeutic agents.

FTIR was used to characterize the structures of QU-templated MSNs. The FTIR spectra of QU-templated MSNs are shown in Fig. 5. The characteristic peaks of about 1115 per centimeter (/cm), 874/cm, and 477/cm are recognizable in the spectra of silica nanostructures and are attributed to the asymmetric and symmetric stretching and bending vibrations of Si–O–Si, respectively, which is quite similar and in accordance with the study of Sarkar *et al.* (Sarkar *et al.*, 2016). The symmetric stretching of Si-OH generated a peak of about 1440/cm. In QU-MSNs, the carbonyl peak of quercetin shifted to 1619/cm because of the binding of MSN with QU. The stretching vibrations of Si-OH groups and QU were also correlated with the peaks of about 3414/cm (Nikolić *et al.*, 2010). The presence of crosslinked QU molecules was confirmed by the peaks in the QU-MSN areas of 2923, 2035, 1619, and 1384/cm, which correlated to aliphatic C–H vibrations and substituted-benzene groups, respectively.

With an EDS (Energy Dispersive X-ray Spectrometer) detector on the SEM, elemental analysis can be performed in addition to imaging the sample surface morphology and structure. The EDS spectrum of nanostructures prepared with QU as a pore-forming agent is shown in Fig. 6. As a result, a high-sensitivity EDS detector was used to trace the elemental EDX spectrum. The dominant constituents of the QU-templated MSNs, namely carbon ©, oxygen (O), nitrogen (N), iron (Fe), zinc (Zn), and silicon (Si), were successfully observed, and indications were employed for line scans and visualization. The binding energies of O and Si are represented by peaks of around 0.5 kV and 1.9 kV, respectively. The weight ratio of silica is 81.1%. The EDS spectrum's remaining lines correspond to the other elements (Au, Fe, and Zn).

Biocompatibility and antibacterial activity of QU-templated MSNs

There was no requirement to extract residual

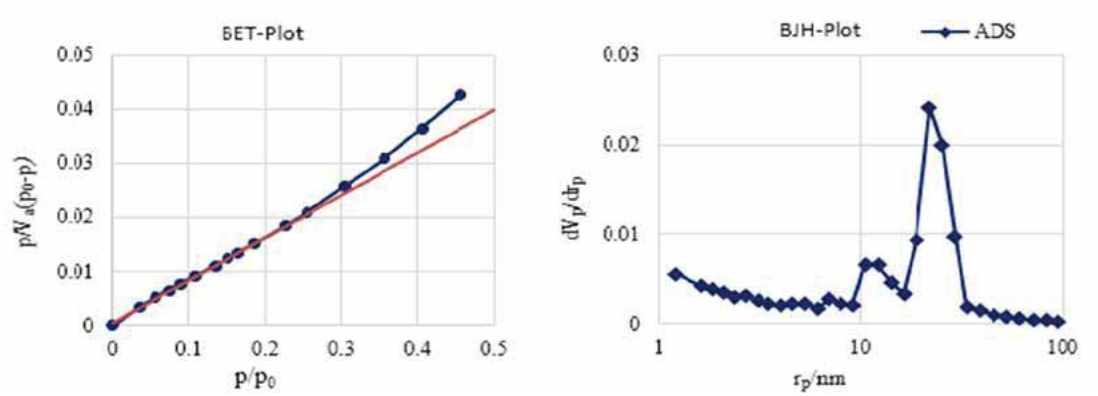


Fig. 4: The QU-templated MSNs pore diameter distribution and N_2 adsorption/desorption isotherm models

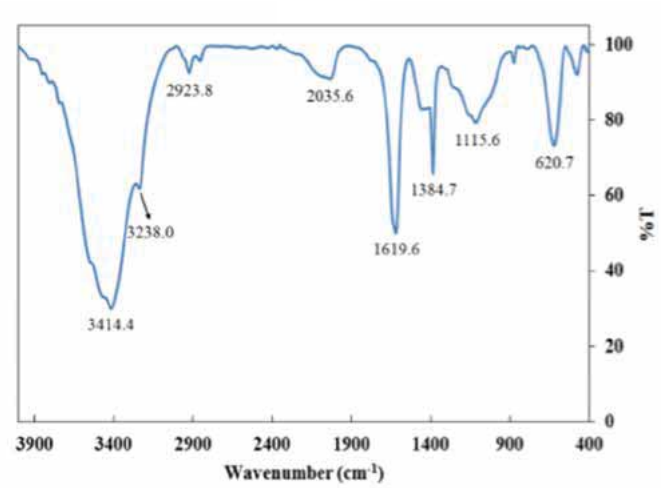


Fig. 5: FTIR spectra of QU-templated MSN

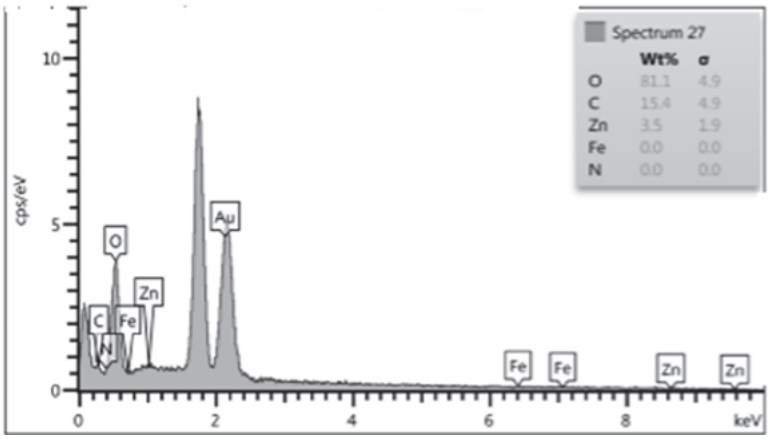


Fig. 6: EDS analysis of synthesized QU-templated MSs

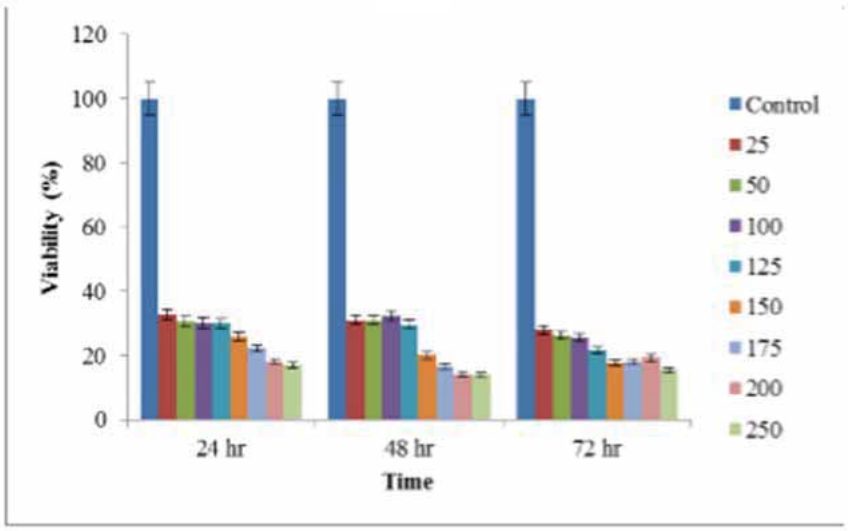


Fig. 7: Cytotoxicity of QU-templated MSNs

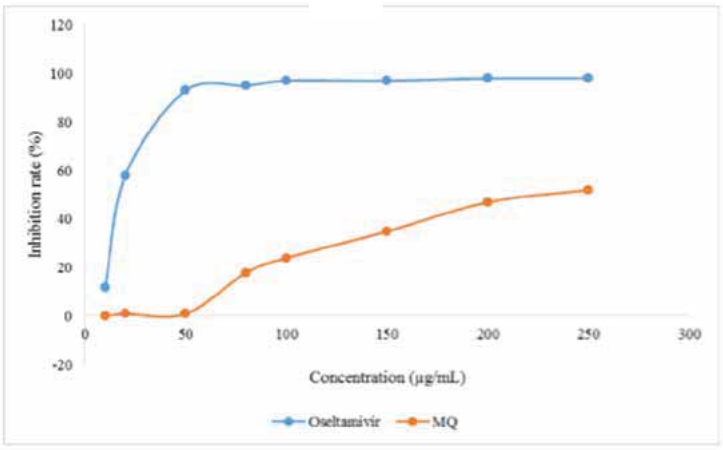


Fig. 8: Antiviral effect of QU-templated MSNs

QU in MSNs because the antioxidant effects of QU might not only shield the oxidation of MSNs but might also contribute to the antibacterial effect. Toxicity substantially impaired the additional efficacy of the nano-medicine within the biomedical field. According to Fig. 7, QU-templated MSNs are significantly biocompatible and non-toxic in different concentrations of 25, 50, 75, 100, 125, 150, 175, and 200 mg/mL in different time periods of 24, 48, and 72 h. Cell culture survival did not change significantly, and QU-templated MSNs showed tremendous biocompatibility properties. In the realm of biomedicine, these nanoparticles exhibit remarkable potential attributed to their high levels of biocompatibility and the absence of toxic side effects. Additionally, they are capable of effectively loading and transporting a variety of pharmaceutical and biological substances.

Oseltamivir is an antiviral drug applied to treatment and inhibition of influenza B and influenza A. It tends to make health problems less painful and reduce healing time by 1 to 2 days. As shown in Fig. 8, with the increase in the concentration of this drug against the viral cell population, the percentage of inhibition increases significantly. When the concentration level is raised, QU-templated MSNs eventually exhibit

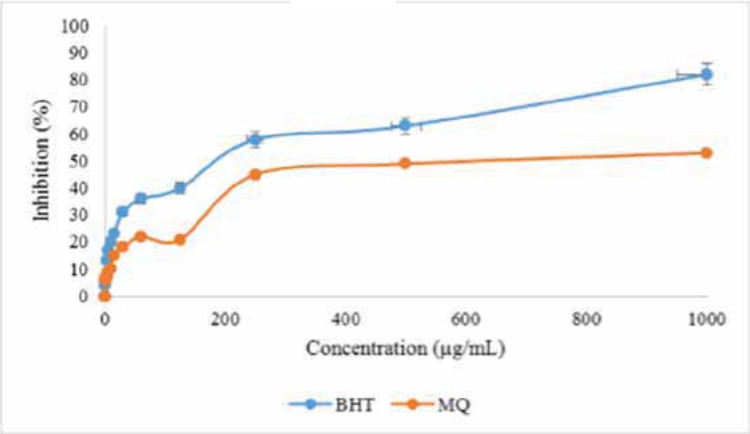


Fig. 9: Antioxidant activity of QU-templated MSNs

inhibitory effects against viral agents and have antiviral and inhibitory effects similar to those of Oseltamivir (Fig. 8).

In the Anti-DPPH assay, QU-templated MSNs, similar to BHT, show strong anti-radical effects by increasing their concentration and can provide remarkable therapeutic capacity in various clinical applications (Fig. 9).

The complete morphologic mechanism of MSNs synthesized by polyphenols (tannic acid, quercetin, Gallic acid, ethyl gallate, and eudesmic acid) was investigated. Lou *et al* reported that polyphenols have different behavior on the final size of nanoparticles regarding protein kinase A (pKa); therefore, the lower pKa leads to the synthesis of magnificent MSNs. It seems that the presence of functional groups has a key role in growing nanoparticles. To this aim, QU is able to interact with hydrogen bonds (Luo *et al.,* 2019). Naturally occurring silica, especially present in agricultural residues, serves as an alternative source for the expensive commercial silica precursors required for the synthesis of MSNs. Rice husk, a byproduct of agriculture, is most often used to produce valuable derivatives and silica goods (Pode, 2016). Another important crop grown worldwide is maize, which produces 785 million tonnes of biomass annually, with more than 60% of the biomass being silica (Kumar *et al.,* 2010). Usgodaarachchi *et al.* used the sol-gel technique to create amorphous silica mesoporous nanoparticles 50–60 nm in high purity from rice husks (Usgodaarachchi *et al.,* 2021). Porrang *et al.* (2021) created MSNs from natural sources such as rice husks and wheat. Porous silica nanoparticles are innovative sources of pharmaceuticals and have been employed as carriers of different drugs to treat different types of cancer, lessen medication toxicity, and deliver the drug to a particular site of action while still affecting other parts of the body (He *et al.,* 2020). Other applications for silica mesoporous nanoparticles include vascular tissue engineering (Shokry *et al.,* 2015), wound healing and antibacterial activities (Chen *et al.,* 2021), stem cell research (Rosenbrand *et al.,* 2018; Vafa *et al.,* 2021), and stem cell labeling (Rosenbrand *et al.,* 2018). Although antioxidant chemicals are essential for the management or prevention of many acute illnesses, including cancer, scientists face significant challenges because of their extreme instability and solubility. Then, The choice of an effective carrier can contribute to the stability of the circulatory system while minimizing unwanted interactions (Vafa and Bazargan-Lari, 2021). The salient bioavailability of MSNs makes them suitable to medical applications as potential carriers (Iraji *et al.,* 2015).

CONCLUSION

The study results revealed the mechanism by which QU forms a macromolecular framework anchored to silica, serving as a template for MSNP formulation. QU's structure results in irregular pore spaces. Using small-angle x-ray scattering, detailed data was acquired on the constituents, particularly the porous nature of the resulting MSNs. For the first time, the particle dimensions and pore formation

are regulated by the macromolecular structure of the templates. The role of QU in the morphogenetic function of MSNs has been extensively investigated, with characterization performed using TEM, SEM, XPS, XRD, and BET methods. The findings indicate that the inclusion of QU leads to a gradual increase in crystallite size, especially compared to non-mesoporous nanostructures. The QU supramolecular framework acts as a scaffold for silica precursors to polymerize around, creating pores. In addition, the production of QU-templated mesoporous silica nanostructures (QU-MSNs) were shown to possess specific pore morphology, large pore diameters, and relatively small average particle sizes. QU served as a non-surfactant, neutral template in an ammonia and ethanol mixture, resulting in approximately spherical particles with monodisperse diameters of about 180 nm. The preparation of QU-MSNs offers numerous advantages over traditional MSNs. n contrast to conventional surfactant templates, QU is characterized by its safety and non-toxic nature, making it especially advantageous for use in biomedical applications. For large-scale manufacturing, it is preferable to use a straightforward one-pot synthesis using a cheap and abundant template that can be easily extracted with water. Furthermore, the findings indicated that QU-templated MSNs exhibit inhibitory and antimicrobial activities comparable to Oseltamivir, showing increased inhibitory effects on microbial agents with higher concentrations. Like BHT, QU-templated MSNs demonstrate significant antioxidant effects when their concentration is increased and also show exceptional therapeutic potential in various clinical applications. Overall, QU-templated MSNs represent a unique type of mesoporous silica nanomaterial characterized by uniform scale, unique structure, small dimensions, and high mesoporosity, making them ideal for encapsulating biomacromolecules and drug delivery systems. The findings contribute to the development of QU-MSNs for relevant biomedical applications by elucidating the morphogenetic process of MSNs through polyphenols. This sample is particularly appropriate for drug delivery applications, supported by its interconnected architecture, which has been validated through drug release and uptake experiments. The study's focus on QU as the sole morphogenetic agent may limit the generalizability of the findings to other polyphenols, potentially overlooking alternative compounds that could offer enhanced templating properties. In addition, while various characterization techniques were employed, the absence of dynamic light scattering (DLS) restricts a comprehensive understanding of the particle size distribution and stability. The reliance on in vitro assessments without accompanying in vivo studies raises questions about the nanoparticles' safety and efficacy in biological systems. Moreover, while the synthesis method's environmental benefits are underscored, a thorough life-cycle assessment is necessary to completely understand the ecological effects of these nanoparticles throughout their lifecycle. Future research should investigate a broader range of polyphenols and natural compounds to identify additional effective morphogenetic agents for synthesizing mesoporous silica nanoparticles. Conducting in vivo studies will be essential to validate the therapeutic potential and biocompatibility of QU-templated nanoparticles, providing insights into their pharmacokinetics and safety in living organisms. Furthermore, clarifying the molecular mechanisms that regulate the interaction between QU and silica precursors will deepen our understanding and may improve the synthesis process. Finally, optimizing synthesis conditions, such as pH and temperature, could lead to nanoparticles with improved properties, enhancing their effectiveness in drug delivery applications.

AUTHOR CONTRIBUTIONS

A. Zare Hoseinabadi performed formal analysis, data acquisition, investigation, visualization, and writing original draft preparation. E. Rafiei Taqanaki performed formal analysis, data acquisition, investigation, visualization, and writing original draft preparation. A.M. Amani performed Conceptualization, Methodology, Supervision, Writing, reviewing and editing. S. Hafez Ghoran performed Conceptualization, Methodology, Supervision, Writing, reviewing and editing. H. Kamyab performed the experiments and literature review, compiled the data and manuscript preparation. A. Razmfarsa performed the experiments and literature review, compiled the data and manuscript preparation. E. Khalili performed formal analysis, data acquisition, investigation and visualization. M. Yusuf performed formal analysis, data acquisition, investigation and visualization. S. Rajendran performed formal analysis, data acquisition, investigation and visualization. All

authors read and approved the final version of the manuscript.

ACKNOWLEDGEMENT

The authors wish to thank Shiraz University of Medical Sciences for the technical support of this study. Also, the researcher extends gratitude to the Kavir Group Pty Ltd for their invaluable support and collaboration as a research support executive, contributing significantly to the success of this research.

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

©2024 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, if 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 affiliations.

ABBREVIATIONS

%	Percentage value
°C	Degree Celsius
ANOVA	*Analysis of variance*
Au	*Gold*
BET	Brunauer–emmett teller
BHT	Butylated hydroxytoluene
BJH	Barrett-joyner-halenda
C	*Carbon*
CFU	*Colonogenic cell numbers*
CLSI	Clinical and laboratory standard institute
CTAB	Cetyltrimethylammonium bromide
DPPH	2,2-diphenyl-1-picrylhydrazyl
EDS and EDX	Energy-dispersive X-ray spectroscopy
EDS and EDX	Energy-dispersive X-ray spectroscopy
FCC	Face center cubic
Fe	*Iron*
FT-IR	Fourier transform infrared
g	Gram
H_2O_2	Hydrogen peroxide
h	Hour
LB	Lactose broth
MBC	Minimum bactericidal concentration
CFU	McFarland's standard
Mg/mL	Microgram per milliliter
MIC	Minimum inhibitory concentration
mL	Milliliters
MSNs	Mesoporous silica nanoparticleS
MTT	*3-4, 5-dimethylthiazolyl-2-2, 5-diphenyltetrazolium bromide*
N	*Nitrogen*
Na_2CO_3	*Sodium carbonate*

NB	Nutrient broth
O	Oxygen
PBS	Phosphate-buffered saline
pH	Potential of hydrogen
PKa	*Protein kinase A*
QU	Quercetin
rpm	Revolutions per minute
SAXS	Small angle x-ray scattering
SEM	Scanning electron microscopy
SPSS	Social Sciences Statistics Package
Si	*Silicon*
TEM	Transmission electron microscopy
TEOS	Tetraethoxysilane
WAXRD	Wide-angle X-ray diffraction
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction analysis
Zn	*Zinc*

REFERENCES

Abbas, M.; Saeed, F.; Anjum, F.M.; Afzaal, M.; Tufail, T.; Bashir, M. S.; Suleria, H.A.R., (2017). Natural polyphenols: An overview. Int. J. Food Prop., 20: 1689-1699 **(11 pages).**

Sarkar, A.; Ghosh, S.; Chowdhury, S.; Pandey, B.; Sil, P.C., (2016). Targeted delivery of quercetin loaded mesoporous silica nanoparticles to the breast cancer cells. Biochim. Biophys., Acta (BBA)-General Subjects. 1860: 2065-2075 **(11 pages).**

Amani, A.M.; Tayebi, L.; Vafa, E.; Abbasi, M.; Vaez, A.; Kamyab, H.; Bazargan-Lari, R., (2024). On the horizon of greener pathways to travel into a greener future portal: Green MXenes, environment-friendly synthesis, and their innovative applications. J. Cleaner Prod., 140606 **(23 pages).**

Balouiri, M.; Sadiki, M.; Ibnsouda, S.K., (2016). Methods for in vitro evaluating antimicrobial activity: A review. J. Pharm. Anal., 6: 71-79 **(9 pages).**

Chen, J.; Qiu, L.; Li, Q.; Ai, J.; Liu, H.; Chen, Q., (2021). Rapid hemostasis accompanied by antibacterial action of calcium crosslinking tannic acid-coated mesoporous silica/silver Janus nanoparticles. Mater. Sci. Eng., 123: 111958 **(8 pages).**

David, A.V.A.; Arulmoli, R.; Parasuraman, S., (2016). Overviews of biological importance of quercetin: A bioactive flavonoid. Pharmacogn. Rev., 10: 84 **(11 pages).**

Fröba, M.; Köhn, R.; Bouffaud, G.; Richard, O.; van Tendeloo, G., (1999). Fe2O3 nanoparticles within mesoporous MCM-48 silica: in situ formation and characterization. Chem. Mater., 11: 2858-2865 **(8 pages).**

Gao, Z.; Zharov, I., (2014). Large pore mesoporous silica nanoparticles by templating with a nonsurfactant molecule, tannic acid. Chem. Mater., 26: 2030-2037 **(8 pages).**

Ghoran, S.H.; Firuzi, O.; Jassbi, A.R., (2020). Phytoconstituents from the aerial parts of Salvia dracocephaloides Boiss. and their biological activities. J. Env. Treat. Tech., 8: 1274-1278 **(5 pages).**

Han, L.; Che, S., (2013). Anionic surfactant templated mesoporous silicas (AMSs). Chem. Soc. Rev., 42: 3740-3752 **(12 pages).**

He, Y.; Shao, L.; Usman, I.; Hu, Y.; Pan, A.; Liang, S.; Xu, H., (2020). A pH-responsive dissociable mesoporous silica-based nanoplatform enabling efficient dual-drug co-delivery and rapid clearance for cancer therapy. Biomater. Sci., 8: 3418-3429 **(12 pages).**

Iraji, S.; Rashidi, L.; Ganji, F., (2015). Functionalized Mesoporous silica nanoparticles as a novel antioxidant delivery system. Iran J. Chem. Eng., 12: 93 **(11 pages).**

Kioni, P.N.; Gao, Y.; Tang, Z.; Gatebe, E.; Wanyika, H., (2011). Synthesis and characterization of ordered mesoporous silica nanoparticles with tunable physical properties by varying molar composition of reagents. **(9 pages).**

Kumar, S.; Upadhyaya, J.S.; Negi, Y.S., (2010). Preparation of nanoparticles from corn cobs by chemical treatment methods. BioResources. 5: 1292-1300 **(9 pages).**

Lakhanpal, P.; Rai, D.K., (2007). Quercetin: a versatile flavonoid., Int. J. Med. Update. 2: 22-37 **(16 pages).**

Loizzo, M.R.; Tundis, R.; Bonesi, M.; Menichini, F.; De Luca, D.; Colica, C.; Menichini, F., (2012). Evaluation of Citrus aurantifolia peel and leaves extracts for their chemical composition, antioxidant and anti-cholinesterase activities. J. Sci. Food Agric., 92: 2960-2967 **(8 pages).**

Luo, J.; Panzarasa, G.; Osypova, A.; Sorin, F.; Spano, F.; Rossi, R.M.; Boesel, L.F., (2019). Polyphenols as morphogenetic agents for the controlled synthesis of mesoporous silica nanoparticles. Chem. Mater., 31: 3192-3200 **(9 pages).**

Maldonado, M.; Carmona, M.C.; Velásquez, Z.; Puig, A.; Cruzado, A.; López, A.; Young, C.M., (2005). Siliceous sponges as a silicon sink: an overlooked aspect of benthopelagic coupling in the marine silicon cycle.

Limnol. Oceanogr., 50: 799-809 **(11 pages).**

Matshitse, R., (2010). Brunauer-Emmett-Teller (BET) surface area analysis. Rhodes Univ. Natl. Res. Found., 384 **(7 pages).**

Nikolić, M.; Giannakopoulos, K.P.; Srdić, V.V., (2010). Synthesis and characterization of mesoporous silica core-shell particles. Process. Appl. Ceram., 4: 81-85 **(5 pages).**

Pang, J. B.; Qiu, K.Y.; Wei, Y., (2001). A new nonsurfactant pathway to mesoporous silica materials based on tartaric acid in conjunction with metallic chloride. Chem. Mater., 13: 2361-2365 **(5 pages).**

Pang, J.B.; Qiu, K. Y.; Wei, Y., (2001). Preparation of mesoporous silica materials with non-surfactant hydroxy-carboxylic acid compounds as templates via sol–gel process. J. Non-Cryst. Solids, 283: 101-108 **(8 pages).**

Pode, R., (2016). Potential applications of rice husk ash waste from rice husk biomass power plant. Renew. Sustainable Energy Rev., 53: 1468-1485 **(18 pages).**

Porrang, S.; Rahemi, N.; Davaran, S.; Mahdavi, M.; Hassanzadeh, B., (2021). Preparation and in-vitro evaluation of mesoporous biogenic silica nanoparticles obtained from rice and wheat husk as a biocompatible carrier for anti-cancer drug delivery. Eur. J. Pharm. Sci., 163: 105866 **(8 pages).**

Riesgo, A.; Taboada, S.; Kenny, N.J.; Santodomingo, N.; Moles, J.; Leiva, C.; Maldonado, M., (2021). Recycling resources: silica of diatom frustules as a source for spicule building in Antarctic siliceous demosponges. Zool. J. Linn. Soc., 192: 259-276 **(18 pages).**

Rosenbrand, R.; Barata, D.; Sutthavas, P.; Mohren, R.; Cillero-Pastor, B.; Habibovic, P.; van Rijt, S., (2018). Lipid surface modifications increase mesoporous silica nanoparticle labeling properties in mesenchymal stem cells. Int. J. Nanomed., 7711-7725 **(15 pages).**

Sarkar, A.; Ghosh, S.; Chowdhury, S.; Pandey, B.; Sil, P.C., (2016). Targeted delivery of quercetin loaded mesoporous silica nanoparticles to the breast cancer cells. Biochim. Biophys. Acta. Biophys., (BBA)-General Subjects. 1860: 2065-2075 **(11 pages).**

Shokry, H.; Vanamo, U.; Wiltschka, O.; Niinimäki, J.; Lerche, M.; Levon, K.; Sahlgren, C., (2015). Mesoporous silica particle-PLA–PANI hybrid scaffolds for cell-directed intracellular drug delivery and tissue vascularization. Nanoscale. 7: 14434-14443 **(10 pages).**

Stevens, W.J.; Lebeau, K.; Mertens, M.; Van Tendeloo, G.; Cool, P.; Vansant, E.F., (2006). Investigation of the morphology of the mesoporous SBA-16 and SBA-15 materials. J. Phys. Chem., 110: 9183-9187 **(5 pages).**

Twentyman, P.R.; Luscombe, M., (1987). A study of some variables in a tetrazolium dye (MTT) based assay for cell growth and chemosensitivity. Br. J. Cancer, 56: 279-285 **(7 pages).**

Usgodaarachchi, L.; Thambiliyagodage, C.; Wijesekera, R.; Bakker, M.G., (2021). Synthesis of mesoporous silica nanoparticles derived from rice husk and surface-controlled amine functionalization for efficient adsorption of methylene blue from aqueous solution. Curr. Res. Green Sustainable Chem., 4: 100116 **(11 pages).**

Vafa, E.; Azizli, M.J.; Tayebi, L.; Amani, A.M.; Kamyab, H., (2024). Integrating bioactive glass with compatibilizer: a novel approach for hard tissue regeneration using PXDDA-co-PLA/PLCL/PGLA nanocomposites. Mater. Chem. Phys., 316: 129070 **(9 pages).**

Vafa, E.; Bazargan-Lari, R., (2021). Bovine serum albumin protected gold nanozymes as a novel anti-cancer nanodrug for acute T-type lymphoblastic leukemia treatment via effect on the expression of anti-apoptotic genes. Appl. Biol. Chem., 64: 86 **(10 pages).**

Vafa, E.; Bazargan-Lari, R.; Bahrololoom, M.E., (2021). Synthesis of 45S5 bioactive glass-ceramic using the sol-gel method, catalyzed by low concentration acetic acid extracted from homemade vinegar. J. Mater. Res. Technol., 10: 1427-1436 **(9 pages).**

Vafa, E.; Tayebi, L.; Abbasi, M.; Azizli, M.J.; Bazargan-Lari, R.; Talaiekhozani, A.; Chelliapan, S., (2023). A better roadmap for designing novel bioactive glasses: effective approaches for the development of innovative revolutionary bioglasses for future biomedical applications. Environ. Sci. Pollut. Res., 30: 116960-116983 **(24 pages).**

Wei, Y.; Jin, D.; Ding, T.; Shih, W.H.; Liu, X.; Cheng, S.Z.; Fu, Q., (1998). A non-surfactant templating route to mesoporous silica materials. Adv. Mater., 10: 313-316 **(4 pages).**

Wei, Y.; Xu, J.; Dong, H.; Dong, J.H.; Qiu, K.; Jansen-Varnum, S.A., (1999). Preparation and physisorption characterization of d-glucose-templated mesoporous silica sol–gel materials. Chem. Mater., 11: 2023-2029 **(7 pages).**

Xu, Y.; Xu, S.; Emmler, T.; Roelofs, F.; Boettcher, C.; Haag, R.; Buntkowsky, G., (2008). A novel green template for the synthesis of mesoporous silica. Chem. Eur. J., 14: 3311-3315 **(5 pages).**

Zhao, D.; Feng, J.; Huo, Q.; Melosh, N.; Fredrickson, G.H.; Chmelka, B.F., Stucky, G.D., (1998). Triblock copolymer syntheses mesoporous silica with periodic 50 to 300 angstrom pores. science, 279: 548-552 **(5 pages).**

Zheng, J.Y.; Pang, J.B.; Qiu, K.Y.; Wei, Y., (2002). Synthesis of mesoporous silica materials via nonsurfactant templated sol-gel route by using mixture of organic compounds as template. J. Sol-Gel. Sci. Technol., 24: 81-88 **(8 pages).**

AUTHOR (S) BIOSKETCHES

Zare Hoseinabadi, A.R., Ph.D., Assistant Professor, Department of Medical Nanotechnology, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran
- Email: *ar.zare00@gmail.com*
- ORCID: 0000 0001 7297 8065
- Web of Science ResearcherID: ADX-2248-2022
- Scopus Author ID: 55795600300
- Homepage: https://scholar.google.com/citations?user=8hgcHPUAAAAJ&hl=en

Rafiei Taqanaki , E., Ph.D., Assistant Professor, Department of Medical Nanotechnology, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran
- Email: *erafie@rocketmail.com*
- ORCID: 0000-0002-3061-9758
- Web of Science ResearcherID: IZP-6822-2023
- Scopus Author ID: 55468022900
- Homepage: https://scholar.google.com/citations?user=JzBtDRYAAAAJ&hl=en

Hafez Ghoran, S., Ph.D. Candidate, Department of Medical Nanotechnology, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran.
- Email: *s_Hafezghoran@yahoo.com*
- ORCID: 0000-0002-3061-9754
- Web of Science ResearcherID: ABD-9876-2020
- Scopus Author ID: 57195483722
- Homepage: https://www.webofscience.com/wos/author/record/2122428

Amani, A.M., Ph.D., Associate Professor, Department of Medical Nanotechnology, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran
- Email: *amani_a@sums.ac.ir*
- ORCID: 0000-0002-5965-1575
- Web of Science ResearcherID: AAP-1567-2021
- Scopus Author ID: 56355136200
- Homepage: https://typeset.io/authors/ali-mohammad-amani-2he5flobw5

Kamyab, H., Ph.D., Assistant Professor, [1]Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia. [2]Universidad UTE, Centro de Investigación en Salud Públicay Epidemiología Clínica (CISPEC), Quito 170527, Ecuador. [3]Department of Biomaterials, Saveetha Dental College, and Hospital, Saveetha Institute of Medical and Technical Sciences, Chennai, 600 077, India.
- Email: *hesam_kamyab@yahoo.com*
- ORCID: 0000-0002-5272-2297
- Web of Science ResearcherID: H-4583-2016
- Scopus Author ID: 55355146400
- Homepage: https://www.webofscience.com/wos/author/record/H-4583-2016

Razmfarsa, S., Ph.D. Candidate, Faculty of Science, Department of Biology and Genetics, Islamic Azad University, Mashhad Branch, Razavi Khorasan, Iran
- Email: *razmfarsaatoosa@gmail.com*
- ORCID: 0009-0009-0535-6464
- Web of Science ResearcherID: SD-9676-2023
- Scopus Author ID: 60105149
- Homepage: https://www.linkedin.com/in/atoosa-razmfarsa-2445a3328/?originalSubdomain=ir

Khalili, E., Ph.D., Assistant Professor, Department of Electrical and Engineering, Faculty of Engineering and Physical Science, Centre of Vision Speech and Processing, University of Surrey, United Kingdom
- Email: elhambakhtiari1986@gmail.com
- ORCID: 0000-0002-7955-7068
- Web of Science ResearcherID: G-8333-2019
- Scopus Author ID: 56845475300
- Homepage: https://scholar.google.com/citations?user=iWm-jkEAAAAJ&hl=en

Yusuf, M., Ph.D., Assistant Professor, Clean Energy Technologies Research Institute, Process Systems Engineering, Faculty of Engineering and Applied Science, University of Regina, Canada
Centre of Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India
- Email: *mohd.yusuf@uregina.ca*
- ORCID: 0000-0003-2442-5161
- Web of Science ResearcherID: AAY-2977-2021
- Scopus Author ID: 57220490203
- Homepage: https://www.linkedin.com/in/dr-mohammad-yusuf-3a4b9397?utm_source=share&utm_campaign=share_via&utm_content=profile&utm_medium=android_app

AUTHOR (S) BIOSKETCHES

Rajendran, S., Ph.D., Professor, Institute de Alta Investigación, Universidad de Tarapacá, Arica 1000000, Chile.
- Email: *saravanan3.raj@gmail.com*
- ORCID: 0000-0002-3771-4694
- Web of Science ResearcherID: J-3287-2014
- Scopus Author ID: 7004886581
- Homepage: https://www.webofscience.com/wos/author/record/1203114

HOW TO CITE THIS ARTICLE

Zare Hoseinabadi, A.R.; Rafiei Taqanaki, E.; Hafez Ghoran, S.; Amani, A.M.; Kamyab, H.; Razmfarsa, A.; Khalili, E.; Yusuf, M.; Rajendran, S., (2024). Environmentally friendly synthesis of nanoporous silica materials using quercetin as a morphogenetic agent. Global J. Environ. Sci. Manage., 10(SI): 137-152.

DOI: 10.22034/gjesm.2024.10.SI.09

URL: https://www.gjesm.net/article_716241.html

Global J. Environ. Sci. Manage. 10(SI): 153-166, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

ORIGINAL RESEARCH PAPER

Validation of heavy metals in geothermal to support water management practices and mitigation strategies

G.M. Idroes[1,2], D.P. Rezeki[3], K. Khairi[3], K. Khairan[4], R. Idroes[4], E. Suhartono[5], R. Prasetio[6], S.A. Rahman[7], S. Suhendrayatna[8,9*]

[1] *Graduate School of Mathematics and Applied Sciences, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia*

[2] *Department of Occupational Health and Safety, Faculty of Health Sciences, Universitas Abulyatama, Aceh Besar 23372, Indonesia*

[3] *Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*

[4] *Department of Pharmacy, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*

[5] *Department of Medical Chemistry/ Biochemistry, Faculty of Medicine, Lambung Mangkurat University, Banjarbaru 70124, Indonesia*

[6] *Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia*

[7] *Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Persiaran Tun Khalil Yaakob, 26300 Gambang, Kuantan, Pahang, Malaysia*

[8] *Biochar and Forest Conservation Research Center, Universitas Syiah Kuala, Banda Aceh, Indonesia*

[9] *Department of Chemical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*

ARTICLE INFO

Article History:
Received 18 June 2024
Revised 23 August 2024
Accepted 02 October 2024

Keywords:
Environmental contamination risks
Flame atomic absorption spectroscopy (FAAS)
Heavy metal analysis
Water quality assessment

DOI: 10.22034/gjesm.2024.10.SI.10

ABSTRACT

BACKGROUND AND OBJECTIVES: This study aimed to evaluate and validate the concentrations of six heavy metals, specifically lead, cadmium, copper, chromium, zinc, and iron, found in geothermal water from the Mount Kembar Region in Gayo Lues Regency, Aceh Province. This study primarily sought to investigate the health risks that these heavy metals may present and to deliver vital information that would aid in the advancement of water management practices and mitigation strategies in the locality. Understanding the levels of these metals is essential for preventing long-term health effects on the local population and ensuring sustainable use of geothermal water resources.

METHODS: Water samples were taken from five geothermal sites in the region and analyzed with flame atomic absorption spectroscopy, a highly effective technique for the detection of trace metals. The flame atomic absorption spectroscopy technique was validated for precision, linearity, and accuracy, achieving R-squared values greater than 0.99, confirming the reliability of the analytical results. This confirmed that the identified concentrations of metals were reliable and could serve to evaluate the possible health risks faced by residents and users of the water source.

FINDINGS: The analysis revealed that copper, chromium, zinc, and iron concentrations were within the permissible limits for safe drinking water as established by national and international health guidelines. However, elevated concentrations of lead and cadmium were detected in multiple sampled locations, surpassing the recommended safety thresholds. This implies a substantial danger to the health of those who drink or are exposed to this water, as both lead and cadmium are associated with severe health complications, including damage to the nervous system and kidneys. The findings underscore the urgent need for targeted water treatment and continuous monitoring, providing critical data to support sustainable water management and mitigation strategies in geothermal regions.

CONCLUSION: The findings of this study underscore the urgent need for water treatment initiatives and continuous monitoring of geothermal water sources in the Mount Kembar Region. Although the analysis showed that the majority of metals were within safe ranges, the notably high levels of lead and cadmium require urgent measures to minimize health risks. Preventive measures, such as water filtration and public health advisories, should be implemented to safeguard the local population from the potential long-term exposure to these toxic metals.

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
1

NUMBER OF TABLES
7

*Corresponding Author:
Email: *suhendrayatna@usk.ac.id*
Phone: +812 6 911 823
ORCID: 0000-0002-2673-0947

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Geothermal energy is a renewable resource obtained from the heat located beneath the Earth's surface (Idroes *et al*., 2024a), primarily produced by volcanic activity and the natural radioactive decay of elements within the Earth's core (Idroes *et al*., 2024b). This thermal energy is extracted by utilizing underground sources of heated water (Shah *et al*., 2024) or steam (Lund and Toth, 2021), enabling the production of electricity or the provision of direct heating for diverse (Owebor *et al*., 2021). One of its key advantages is its ability to offer a consistent and reliable energy supply (Maulidar *et al*., 2024), unlike other renewable sources like solar and wind (Lin *et al.,* 2021), which depend on weather conditions (Lund *et al*., 2022). Geothermal energy is particularly effective in regions with significant geothermal activity (Islam *et al*., 2022), such as Iceland, the United States (Azarpour *et al*., 2022), and New Zealand, and can play a vital role in these areas energy grids (Miranda *et al*., 2020). In addition to being stable, geothermal energy is environmentally friendly (Androniceanu and Sabie, 2022), emitting far fewer greenhouse gases than fossil fuels (Letcher, 2022). Its smaller land footprint compared to solar and wind farms also makes it ideal for regions where space is limited (Sayed *et al*., 2021). However, geothermal development comes with challenges (Kumar *et al*., 2022), particularly the high upfront costs associated with drilling and exploration and its geographical limitations, as it can only be effectively harnessed in specific locations (Santos *et al*., 2022). Despite the existing challenge, geothermal energy remains a viable long-term solution for sustainable energy generation (Bhagaloo *et al*., 2022). It provides significant environmental and economic benefits (Soltani *et al*., 2021) when applied in suitable circumstances (Hardi *et al*., 2024). Countries with significant volcanic activity, such as Iceland (Meirbekova *et al*., 2024), the Philippines, and the United States, have been leaders in successfully tapping into geothermal energy's vast potential (Gutiérrez-Negrín, 2024). By capitalizing on their specific geographical features, these nations have successfully tapped into geothermal resources for the production of electricity and heating (Anderson and Rezaie, 2019), which has significantly bolstered their energy independence and supported environmental sustainability efforts (Sharmin *et al*., 2023). Indonesia, which sits along the Pacific "Ring of Fire," holds the largest geothermal potential globally, with an estimated capacity of approximately 29.5 Gigawatt (Pambudi and Ulfa, 2024). Indonesia's significant geothermal resources are found in multiple geologically dynamic regions, including Sumatra, Java, Bali, and Sulawesi, thereby establishing the nation as an ideal candidate for large-scale geothermal energy initiatives (Pambudi, 2018). Despite possessing the world's largest geothermal potential, Indonesia faces significant barriers to fully utilizing this resource. Technological limitations hinder the efficient extraction and conversion of geothermal energy, while suboptimal policies and regulatory frameworks have slowed geothermal development (Darma, 2016). Environmental concerns arise from heavy metals in geothermal water (Rotich *et al*., 2024), posing risks to local ecosystems if not properly managed (de Jesus, 2016). To effectively tackle these challenges, Indonesia must leverage technological advancements, enhance governmental policies, and implement robust environmental protections. Such measures are essential for the nation to fully realize its geothermal energy potential and make a significant contribution to global renewable energy objectives (Zhang *et al*., 2019). The Aceh Province also has significant geothermal energy potential, particularly in the Seulawah (Idroes *et al*., 2019) such as Ie Seu'um (Bahri *et al*., 2023), Ie Jue (Aprianto *et al*., 2023) and Jaboi Geothermal areas in Sabang (Idroes *et al*., 2021). These regions are defined by active geothermal features, including fumaroles, hot springs, and volcanic activity, indicating the presence of substantial underground heat sources (Maulydia *et al*., 2024a). The Seulawah Geothermal area, located near the Seulawah Agam volcano, is considered one of the most promising sites for geothermal energy development in Aceh due to its high temperature geothermal reservoirs (Lala *et al*., 2024). The Jaboi Geothermal region located in Sabang has demonstrated significant potential, as research suggests it may be utilized for electricity generation (Rahman *et al*., 2024) as well as for direct use applications (Azhar *et al.,* 2024). Together, these geothermal sites represent a critical opportunity for sustainable energy development in Aceh (Marwan *et al*., 2023), providing an eco-friendly alternative to fossil fuels and also enhances

energy security in the area (Marwan *et al.*, 2023). The geothermal manifestations in this region, such as fumaroles and solfataras, indicate significant geothermal activity (Maulydia *et al.*, 2024b). Located in Gayo Lues, Aceh, Mount Kembar is an area with substantial geothermal potential that has yet to be fully explored. Based on initial hypotheses, this region is believed to contain heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), and zinc (Zn). These heavy metals can pose environmental risks, particularly to people living around the Mount Kembar geothermal area, who may be exposed to heavy metals by consuming contaminated water. The exploration of heavy metal concentrations in geothermal water and their environmental implications is notably underdeveloped. This is a matter of considerable concern, as the presence of heavy metals can result in serious health hazards for humans and contribute to environmental deterioration if not managed appropriately. Additional research is required to better understand the distribution and concentration of heavy metals in this region and their effects on the local ecosystem. The aim of the present study is to measure and analyze the concentrations of heavy metals such as Pb, Cd, Cu, Cr, Fe, and Zn in the geothermal water of the Mount Kembar Region, while assessing the potential environmental impacts of these contaminants on the local ecosystem and communities. This study aims to generate significant scientific information that can enhance the management and sustainable utilization of geothermal resources, with an emphasis on mitigating the environmental and health hazards associated with heavy metals. By studying a geothermal region that has not been thoroughly explored, the study aims to contribute to the broader understanding of heavy metal content in geothermal environments, supporting more effective environmental management practices. This research took place in Aceh Province, Indonesia, in 2024.

MATERIALS AND METHODS

Tools and materials

A thermo scientific iCE 3000 series atomic absorption spectrometer (AAS) in flame mode served as the main instrument for analyzing heavy metal concentrations in geothermal water samples. This instrument was selected due to its ability to accurately measure the concentrations of multiple heavy metals, including Pb, Cd, Cu, Cr, Zn, and Fe. The supporting equipment included a precision balance for accurate sample preparation, a temperature-controlled hotplate for sample preservation, and various glassware items such as beakers, flasks, and pipettes. All chemicals, including nitric acid (HNO_3) and standard solutions for the target metals, were supplied by E. Merck.

Sampling technique

Water samples were collected from five geothermal manifestation points in the Mount Kembar Region, Gayo Lues Regency, Aceh Province, Indonesia, with the coordinates being MK1: 3°46’21” N, 97°35’13” E; MK2: 3°46’19” N, 97°35’13” E; MK3: 3°45’02” N, 97°37’35” E; MK4: 3°45’02” N, 97°37’36” E; and MK5: 3°45’03” N, 97°37’37” E included in Table 1 and illustrated in Fig. 1. The collection of samples was performed with plastic scoops, and these samples were then transferred into polyethylene (PE) bottles that had been pre-cleaned and rinsed first with nitric acid and then with the sample water. The potential of hydrogen (pH) of the samples was adjusted to below 2 with nitric acid to prevent metal precipitation or degradation. They were then kept in a cooler box at 4 ± 2 degrees Celsius (°C) and taken to the laboratory for analysis (BSN, 2004).

Table 1: The water collection sites in the Mount Kembar *Region*

Code	Locations	Coordinate
MK1	Mount Kembar 1	3° 46' 21" N; 97° 35' 13" E
MK2	Mount Kembar 2	3° 46' 19" N; 97° 35' 13" E
MK3	Mount Kembar 3	3° 45' 02" N; 97° 37' 35" E
MK4	Mount Kembar 4	3° 45' 02" N; 97° 37' 36" E
MK5	Mount Kembar 5	3° 45' 03" N; 97° 37' 37" E

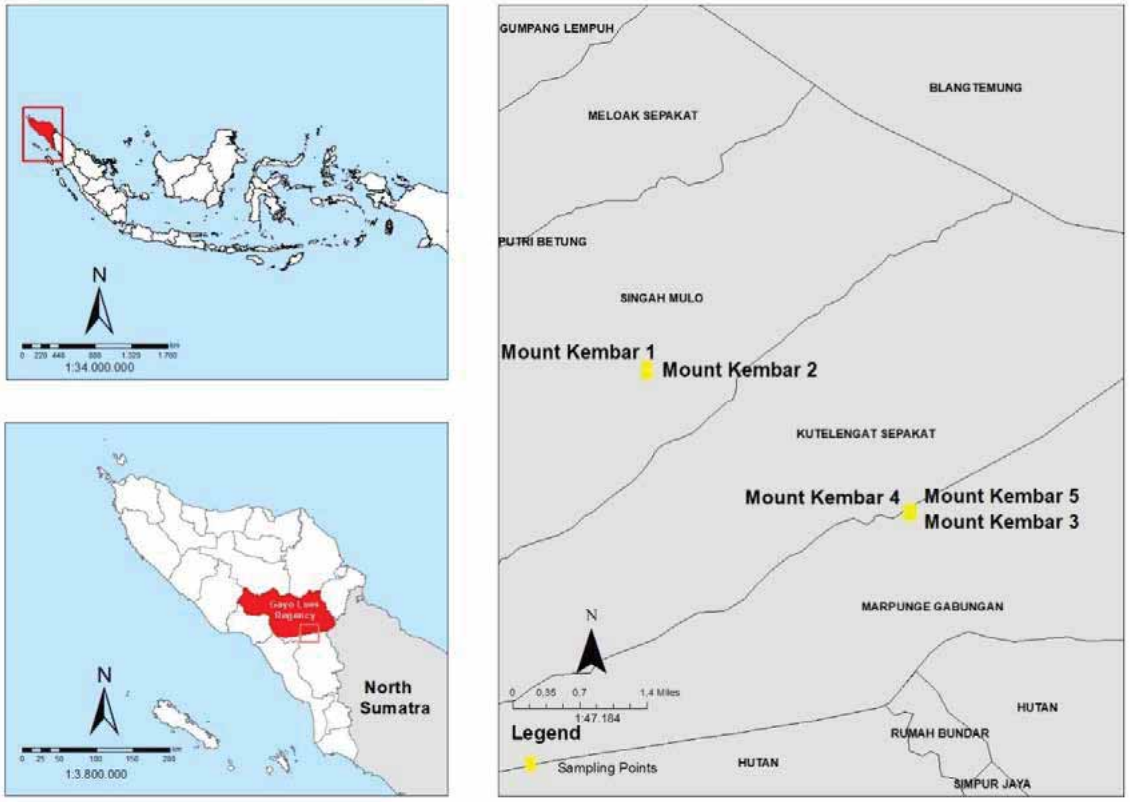


Fig. 1: Geographic position of the study area within the geothermal manifestation of Mount Kembar, located in Gayo Lues Regency, Aceh Province, Indonesia

Sample preparation

The water samples, upon their reception in the laboratory, were subjected to filtration through Whatman No. 42 filter paper to eliminate suspended particulates. The filtered samples were transferred into volumetric bottles for heavy metal analysis using flame atomic absorption spectroscopy FAAS. This filtering step was critical to ensure that only dissolved metals were measured in the analysis (BSN, 2004).

Heavy metal analysis

Flame FAAS was used to quantify the concentrations of six heavy metals. For each metal, calibration standards were formulated from certified stock solutions that have predetermined concentrations. The calibration curve was constructed for each metal using seven different concentration levels, ensuring accuracy across a wide range of metal concentrations prior to the analysis of the samples, the FAAS instrument underwent calibration with standard solutions, and each sample was analyzed in triplicate to guarantee accuracy. The concentrations of the heavy metals were expressed in milligram per liter (mg/L). The FAAS method was validated to confirm the accuracy, precision, linearity, and sensitivity of the measurements. To evaluate the reliability of the method in detecting trace amounts of heavy metals, the limit of detection (LoD) and limit of quantification (LoQ) for each metal were also established (Kassim *et al*., 2022).

Method validation

The method was validated to confirm the accuracy and consistency of the measurements (Idroes *et al*., 2024c). The verification of heavy metal concentrations in geothermal water samples requires the application of multiple critical laboratory methods to ensure both accuracy and reliability in

Table 2: The method for calculating measurement uncertainty

Name	Formula	Sources
Standard deviation (SD) of regression (Sr)	$S_r = \sqrt{\frac{S_{yy} - m^2 S_{xx}}{N-2}}$	(Christian *et al.*, 2013)
SD of slope (Sm)	$S_m = \sqrt{\frac{S_y^2}{\sum(X - X_i)}} = \sqrt{\frac{S_y^2}{\sum x_i^2 - (\sum X_i)^2/N}}$	
SD of intercept (Sb)	$s_b = s_y \sqrt{\frac{s_y \sum x_i^2}{N \sum x_i^2 - (\sum x_i)^2}} = s_y \sqrt{\frac{1}{N - \frac{(\sum x_i)^2}{\sum x_i^2}}}$	
SD of the concentration (Sc)	$S_c = \frac{S_i}{m} \sqrt{\frac{1}{M} + \frac{1}{N} + \frac{(Y_c - Y_{ave})^2}{m^2 S_{xx}}}$	
LoD	$\text{LoD} = 3.3 \times \frac{S_r}{\text{slope}}$	
LoQ	$\text{LoQ} = 10 \times \frac{S_r}{\text{slope}}$	

the results obtained. Atomic absorption spectroscopy (AAS) is utilized to measure the concentrations of metals, with calibration achieved through standard solutions of known concentrations. Calibration curves are constructed for each metal, showing strong linearity with R^2 values above 0.99. The assessment of recovery rates (%Recovery) is conducted through the analysis of spiked samples, in which specific amounts of metals are introduced, serving to confirm the method's precision. The sensitivity of the method, especially for trace metal detection, is determined by key parameters like the LoQ and LoD. The verification of precision is achieved through the repetition of measurements, while the estimation of method uncertainty incorporates potential errors. This validation framework ensures accurate, reliable measurements of heavy metals in geothermal water samples (Christian *et al.*, 2013). The corresponding equations are provided in Table 2.

Determination of the concentration

Standard deviation (SD) values and statistical data represented the uncertainty in the concentration measurement for each parameter. The dataset was utilized to conduct a linear regression analysis employing the least squares method (LINEST) in Microsoft Excel, aiming to determine the optimal line of fit for the provided data. These calculations yielded statistical outputs, including the regression standard deviation (Sr), coefficient of determination (R), slope (m) along with its standard deviation (Sm), intercept (b) with its standard deviation (Sb), and the concentration standard deviation (Sc) (Christian *et al.*, 2013). Table 2 provides a comprehensive overview of the equations employed for determining the standard deviation and other statistical functions.

RESULTS AND DISCUSSION

The in situ examination of water samples included measuring various parameters, such as temperature, salinity, total dissolved solids (TDS), pH, and electrical conductivity (EC) (Andres *et al.*, 2018). The specified parameters yield essential insights into the chemical and physical characteristics of water, facilitating the evaluation of its quality and appropriateness for diverse applications, including potable use, agricultural irrigation, and industrial purposes. The pH level indicates the acidity or alkalinity of the water, while TDS refers to the concentration of dissolved particles. Electrical conductivity (EC) is closely related to TDS, reflecting the water's ability to conduct electricity, which increases with higher ion concentrations (McCleskey *et al.*, 2023). The influence of temperature on other environmental variables is substantial, whereas salinity provides a measurement of total salt content, which is a key indicator for determining water quality in both freshwater and marine environments (Paepae *et al.*, 2021). The results from this comprehensive in situ analysis, which offer a detailed snapshot of the water's condition at the time of sampling, are presented in Table 3. This table consolidates the values recorded

Table 3: On-site data from water samples gathered in the field

Code	T ± SD (◦C)	pH ± SD	EC ± SD Microsiemens per centimeter (µS/cm)	TDS ± SD (mg/L)	Salinity ± SD (‰)
MK1	38.54 ± 0.080	6.30 ± 0.0080	2.43 ± 0.01	386 ± 1.60	0.91 ± 0.030
MK2	45.80 ± 0.008	5.71 ± 0.0008	2.89 ± 0.01	326 ± 0.70	1.39 ± 0.008
MK3	53.76 ± 0.020	6.65 ± 0.0040	3.75 ± 0.01	2083 ± 1.14	1.50 ± 0.007
MK4	87.42 ± 0.140	6.34 ± 0.0040	4.67 ± 0.01	4046 ± 0.40	2.49 ± 0.008
MK5	89.59 ± 0.08	6.26 ± 0.0010	4.77 ± 0.02	4062 ± 0.90	2.59 ± 0.008

for each parameter, thereby enabling comparisons across diverse samples or locations and illuminating potential environmental or contamination-related issues.

The analysis of water samples from five geothermal points (MK1 to MK5) at Mount Kembar in Table 3 reveals variations in critical parameters such as temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), and salinity. The recorded temperatures varied between 38.54°C and 89.59°C, substantially surpassing the acceptable limits for potable water, which suggests considerable geothermal activity in the area. The pH levels were slightly acidic at most points, with values between 5.71 and 6.65, except for MK3, which met the minimum standard of 6.5 outlined in Regulation of the Minister of Health No. 492/2010 for drinking water (Kementerian Kesehatan, 2010). Electrical conductivity showed significant mineral presence, especially at MK4 and MK5, further confirmed by the high TDS values, which ranged from 326 mg/L at MK2 to over 4000 mg/L at MK5. According to Regulation of the Minister of Health No. 492/2010, the maximum acceptable TDS for drinking water is 500 mg/L, meaning only MK1 and MK2 meet this requirement. The elevated TDS and salinity values, particularly at MK3, MK4, and MK5, suggest high mineral content, possibly from geothermal processes, making the water unsuitable for direct human consumption without treatment. Further corroboration is found in the elevated salinity levels, with MK5 demonstrating a concentration of 2.59 percent (%), indicative of a considerable amount of dissolved salts. While the water from MK1 and MK2 may have the potential for limited use after treatment, the remaining points would require extensive purification. Notwithstanding this, the geothermal properties identified suggest a promising opportunity for energy generation or various industrial uses, thereby necessitating additional investigation and evaluation of this resource. In geothermal regions like Mount Kembar, geothermal water, often containing elevated levels of heavy metals such as Pb and Cd, can flow into rivers used by local communities for drinking and daily activities. This contamination poses serious health risks, including neurological and kidney damage. The study emphasizes the necessity for persistent monitoring and the implementation of effective water treatment strategies to avert exposure to heavy metals.

Uncertainty measurement

Critical factors in establishing the accuracy and reliability of the analytical method include the linearity and uncertainty of the calibration curve. The calibration curve establishes a quantitative correlation between the response of the instrument and the concentration of the analyte. The linearity of the calibration curve for each metal ion was evaluated by calculating the slope, intercept, and coefficient of determination (R^2). To gain a clearer understanding of the method's precision, uncertainties pertaining to the slope and intercept were assessed. The following table summarizes the slope, intercept, SD of the slope and intercept, coefficient of determination (R^2), SD of regression, sum of squares regression, and sum of square residual for six metal ions: Cd, Pb, Cu, Cr, Zn, and Fe (Table 4).

The results in Table 4 demonstrate that the calibration curves for all the analyzed metals (Cd, Pb, Cu, Cr, Zn, and Fe) exhibit excellent linearity, as reflected by high R^2 values above 0.99, indicating a strong correlation between instrument response and analyte concentration. The slope values exhibit variability among the different metals, indicating distinct levels of sensitivity. The intercepts are close to zero, suggesting minimal response at zero concentration and further validating the accuracy of the calibration model. The uncertainties in both the slope and intercept, as represented by their SDs, are

Table 4: The calibration curve heavy metal standards

Name	Results					
	Cd	Pb	Cu	Cr	Zn	Fe
Slope	0.0575	0.0323	0.0973	0.0519	0.0421	0.0529
Intercept	0.0007	-0.0014	-0.00003	0.00002	0.00002	-0.000002
SD of slope (Sm)	0.0005	0.0015	0.0010	0.0003	0.0008	0.0007
SD of Intercept (Sb)	0.0004	0.0011	0.0008	0.0002	0.0006	0.0005
Coefficient of determination (R^2)	0.9998	0.9935	0.9997	0.9999	0.9990	0.9995
SD of regression (Sr)	0.0004	0.0013	0.0009	0.0002	0.0007	0.0006
Sum of square regression	13369.0558	461.7802	9045.9556	34457.6491	3128.6964	5881.4812
Sum of square residual	3.0000	3.0000	3.0000	3.0000	3.0000	3.0000

Table 5: Detection and quantification limits of heavy metals

Parameter	Heavy metals (mg/L)					
	Cd	Pb	Cu	Cr	Zn	Fe
LoD	0.021	0.113	0.026	0.013	0.043	0.032
LoQ	0.064	0.343	0.077	0.040	0.132	0.096

minimal, reflecting the precision and consistency of the method. The sum of square regression values being much higher than the sum of square residuals confirms that most variations in the data are well-explained by the regression model. Overall, the data demonstrate that the calibration curves are dependable, showing low levels of uncertainty, which reinforces the robustness of this method for the accurate detection and quantification of the designated metal ions.

Limit of detection and limit of quantification

The LoD and limit of quantification LoQ are key factors in evaluating the sensitivity of an analytical technique. The LoD represents the minimum concentration of a substance that can be detected with confidence, even if it cannot be accurately measured. Conversely, LoQ specifies the minimum concentration that can be accurately and precisely measured. These limits are important for evaluating the method's capacity to detect and quantify trace levels of heavy metals in samples. The LoD and LoQ were determined for six heavy metals: Cd, Pb, Cu, Cr, Zn, and Fe, as presented in Table 5.

The results in Table 5 demonstrate the detection limits (LoD) and quantification limits (LoQ) for six heavy metals, where chromium (Cr) shows the lowest values at 0.013 mg/L for LoD and 0.040 mg/L for LoQ, highlighting the method high sensitivity in detecting and quantifying Cr at low concentrations. Conversely, Pb exhibits the highest LoD and LoQ values, at 0.113 mg/L and 0.343 mg/L, indicating that higher concentrations of Pb are required for reliable detection and quantification. These findings imply that the method is adequately sensitive for identifying and measuring trace concentrations of heavy metals, with sensitivity varying according to the specific type of metal analyzed. The LINEST function in Microsoft Excel was used to calculate the LoD and LoQ values, based on calibration curve data, ensuring an accurate assessment of the method's sensitivity and precision for detecting and quantifying the heavy metals at low concentrations.

Precision and accuracy

The assessment of the analytical method's precision and accuracy was conducted by examining the percentage recovery (% Recovery) and the relative standard deviation (RSD) for the analyzed heavy metals. The results imply that the method demonstrates a high degree of sensitivity for both the detection and quantification of trace amounts of heavy metals, with sensitivity levels differing based on the specific metal analyzed. Table 6 presents the %Recovery and RSD values for the six heavy metals (Pb, Cd, Cu, Cr, Zn, Fe).

As shown in Table 6, the %Recovery for the samples, which were spiked with 30 µg/L standard solutions of

Fe, Cr, Cd, Zn, Pb, and Cu, fell within the acceptable range of 70–125%. This indicates that the preparation method used for the samples is appropriate for analyzing these metals. Precision testing with 30 µg/L standard solutions for Cd, Pb, Cu, Cr, Zn, and Fe demonstrated high precision, with a RSD of less than 2% for each metal.

Heavy metals analysis in water samples

The concentrations of Fe, Cr, Cd, Zn, Pb, and Cu in water samples collected from the geothermal manifestation area of Mount Kembar, Aceh, were assessed using the validated method. The analysis revealed that Fe, Cr, Cd, Zn, Pb, and Cu were present in all the water samples at different levels (as shown in Table 7).

The concentrations of heavy metals, namely Pb, Cd, Cu, Cr, Fe, and Zn, found in water samples from five sites (MK1 to MK5) in the geothermal area of Mount Kembar are summarized in Table 7. The measured concentrations were compared to the Clean Water Quality Standards and Drinking Water Quality Standards specified in the Regulation of the Minister of Health of the Republic of Indonesia No. 32/2017 (Kementerian Kesehatan, 2017). The analysis revealed that lead and cadmium levels in most of the samples exceeded the allowed limits for both clean and drinking water, with MK5 showing the highest concentrations of Pb (0.1408 ± 0.178 mg/L) and Cd (0.0126 ± 0.007 mg/L), highlighting a significant health risk if consumed without proper treatment. In contrast, the levels of copper, chromium, iron, and zinc were found to be within the permissible limits for drinking water quality. Copper levels, ranging from 0.0065 ± 0.009 mg/L to 0.0126 ± 0.009 mg/L, were well below the maximum allowable limit of 2 mg/L. Similarly, zinc concentrations remained safely under the three mg/L limit for drinking water, with the highest concentration recorded at MK5 (0.0353 ± 0.012 mg/L). Chromium levels across all samples were lower than the drinking water limit of 0.05 mg/L, although MK5 approached this threshold with a concentration of 0.0420 ± 0.004 mg/L. Iron concentrations, while under the drinking water limit of 0.3 mg/L, were highest at MK5 (0.0662 ± 0.012 mg/L), requiring periodic monitoring. A limitation of this study is the use of Flame FAAS for heavy metal analysis. Despite its effectiveness, FAAS is not as sensitive or precise as more advanced analytical techniques, including Inductively coupled plasma optical emission spectroscopy (ICP-OES). ICP-OES could provide more accurate detection of trace metals, offering a broader and more detailed analysis (Hossain *et al*., 2021). Future research would benefit from utilizing ICP-OES to achieve greater precision in assessing contamination levels. The evidence presented in this study suggests that geothermal water from the Mount Kembar Region is not safe for

Table 6: Heavy metal with precision (RSD) and accuracy (recovery) values

Sample	Recovery(%)	RSD
Pb	99.67	0.78
Cd	99.16	0.48
Cu	99.88	0.26
Cr	100.11	0.85
Zn	100.03	0.66
Fe	99.98	0.33

Table 7: Heavy metals concentrations in geothermal water samples

Code	(Pb) Concentration (mg/L) ± Sc	(Cd) Concentration (mg/L) ± Sc	(Cu) Concentration (mg/L) ± Sc	(Cr) Concentration (mg/L) ± Sc	(Fe) Concentration (mg/L) ± Sc	(Zn) Concentration (mg/L) ± Sc
MK1	0.0914 ± 0.109	0.0000 ± 0.0000	0.0085 ± 0.009	0.0170 ± 0.004	0.0303 ± 0.008	0.0258 ± 0.012
MK2	0.1068 ± 0.130	0.0039 ± 0.007	0.0065 ±0.009	0.0228 ±0.004	0.0397 ±0.009	0.0163 ± 0.012
MK3	0.1223 ± 0.152	0.0074 ± 0.007	0.0096 ±0.009	0.0362 ±0.004	0.0265 ±0.009	0.0234 ±0.012
MK4	0.1099 ± 0.135	0.0057 ± 0.007	0.0075 ±0.009	0.0266 ±0.004	0.0624 ±0.011	0.0281 ±0.012
MK5	0.1408 ± 0.178	0.0126 ± 0.007	0.0126 ±0.009	0.0420 ±0.004	0.0662 ±0.012	0.0353 ±0.012

direct human consumption, owing to the concerning levels of lead and cadmium detected. These metals are known to cause severe health issues, including neurological impairments and kidney damage, particularly when consumed over prolonged periods. The significant levels of these hazardous metals emphasize the pressing requirement for swift intervention, necessitating the establishment of robust water treatment solutions and extensive monitoring frameworks. Continuous surveillance of water quality in the region is essential to mitigate the health risks posed by heavy metal contamination. While metals like copper, chromium, zinc, and iron were within safe drinking limits, elevated levels of lead and cadmium are likely due to geothermal activity mobilizing these toxic metals into surface water. A frequent concern in areas with significant geothermal activity is the potential for interactions with the Earth's crust to result in the emission of harmful contaminants. Geothermal fluids can cause corrosion, requiring effective management, while impact assessments often overlook health risks and long-term community effects, highlighting the need for more thorough evaluations (Rotich *et al.*, 2024). Potential mitigation strategies include advanced filtration techniques like ion exchange and reverse osmosis, which are effective but can be costly and resource-intensive. Innovative alternatives such as nanotechnology-based filtration using graphene oxide for more efficient removal, and electrocoagulation, which uses electrical currents to precipitate metals, offer promising solutions with reduced waste and energy demands. Phytoremediation, an environmentally friendly approach that uses plants to absorb heavy metals, provides a cost-effective option for regions with limited infrastructure. Employing a combination of these technologies could lead to improved sustainability and effectiveness in water management within geothermal zones. The observed variations in metal concentrations at different sampling sites imply that geological factors, such as the diversity in mineral composition and the routes taken by geothermal fluids, may substantially affect the distribution and levels of heavy metals present in the water. Addressing these concerns will require a nuanced approach, taking into account both the geothermal processes and the geological diversity of the region. It is equally important to consider the economic and logistical feasibility of the proposed solutions. The formulation of targeted water management strategies necessitates a careful equilibrium between technical efficacy, cost-effectiveness, and practical execution. This approach aims to secure the long-term safety of the local water supply while ensuring that the methods employed are both sustainable and economically feasible for the region.

CONCLUSION

This study successfully achieved its primary objective of evaluating and validating the concentrations of heavy metals in geothermal water from the Mount Kembar Region, with a particular focus on Pb, Cd, Cu, Cr, Fe, and Zn. The analytical method developed for this purpose demonstrated excellent accuracy and precision, with strong linearity ($R^2 > 0.99$), ensuring its reliability for detecting and quantifying these metals in geothermal water samples. The findings indicated that the concentrations of copper, chromium, zinc, and iron fell within the acceptable standards for drinking water; however, the levels of lead and cadmium surpassed the permissible thresholds. This raises significant public health concerns, as exposure to elevated levels of lead and cadmium is associated with serious health risks, including neurological damage and kidney dysfunction. The results highlight the urgent necessity for prompt water treatment measures and continuous surveillance to mitigate the health hazards associated with heavy metal pollution in the area. The method's exceptional sensitivity, particularly in detecting even trace amounts of chromium, provides a valuable advantage for early contamination detection in geothermal environments. This makes the method a powerful tool for environmental monitoring and ensures that harmful levels of metals can be identified promptly. This study presents a validated and highly sensitive method for detecting heavy metals in the relatively underexplored Mount Kembar Region, offering important new insights into the environmental quality of geothermal waters in Aceh Province. The region exhibits considerable geothermal potential that has not been fully harnessed, highlighting the importance of precise evaluations of water quality for the sustainable advancement of its geothermal resources. The study suggests that the elevated levels of lead and cadmium are likely linked to local geothermal activity, which may release these toxic

metals from underground reservoirs into surface water systems. Variations in metal concentrations across different sampling sites suggest that geological factors could be influencing the distribution of these contaminants in the region. Moving forward, future research should prioritize continuous, long-term monitoring of geothermal water quality, particularly in areas with high geothermal activity. Engaging in these monitoring activities would yield valuable insights into the temporal dynamics of heavy metal contamination, ultimately advancing our comprehension of the potential health risks faced by local populations. It is crucial to develop advanced water treatment technologies specifically designed to address the unique challenges of heavy metal contamination in geothermal waters, ensuring both public health protection and the sustainable, safe utilization of geothermal resources in the region. These technologies will play a vital role in promoting environmentally responsible geothermal energy development, aligned with the broader goals of sustainable resource management. Local authorities are required to implement forward-thinking actions to address the risks posed by geothermal activity on water resources. This approach is crucial for safeguarding public health and promoting sustainable development initiatives.

AUTHOR CONTRIBUTIONS

G.M. Idroes contributed to manuscript preparation, conducted data analysis, and interpreted the results. D.P. Rezeki also performed data analysis and assisted with writing the manuscript. K. Khairi was responsible for creating figures and interpreting the results. K. Khairan prepared figures, interpreted results, and contributed to writing the manuscript. R. Idroes participated in result interpretation and manuscript preparation. E. Suhartono contributed by preparing figures and interpreting results. R. Prasetio participated in preparing the manuscript and interpreting the results. S.A. Rahman was involved in figure preparation, result interpretation, and manuscript writing. S. Suhendrayatna, the corresponding author, contributed to manuscript preparation, supervised data analysis, and interpreted the results.

ACKNOWLEDGEMENT

This study was funded by Direktorat Riset, Teknologi, dan Pengabdian Kepada Masyarakat, Direktorat Jenderal Pendidikan Tinggi, Riset, dan Teknologi, Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi and Universitas Syiah Kuala through ”Penelitian Disertasi Doktor” scheme with grant number [094/E5/PG.02.00.PL/2024].

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

©2024 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
µg/L	Micrograms per liter
µS/cm	Microsiemens per centimeter (Unit of conductivity)

AAS	Atomic absorption spectroscopy
Cd	Cadmium
Cr	Chromium
Cu	Copper
EC	Electrical conductivity
FAAS	Flame atomic absorption spectroscopy
Fe	Iron
MK	Mount kembar (Sampling point code)
HNO_3	Nitric Acid
LINEST	Regression analysis using the least squares method
LoD	Limit of detection
LoQ	Limit of quantification
mg/L	Milligrams per liter
Pb	Lead
pH	potential of hydrogen
R^2	Coefficient of determination
RSD	Relative standard deviation
Sb	Standard deviation of intercept
Sc	Standard deviation of concentration
SD	Standard deviation
Sm	Standard deviation of slope
Sr	Standard deviation of regression
Sxx	Sum of squares of the x-values
Syy	Sum of squares of the y-values
T	Temperature
TDS	Total dissolved solids
Zn	Zinc

REFERENCES

Anderson, A.; Rezaie, B., (2019). Geothermal technology: Trends and potential role in a sustainable future. Appl. Energy. 248: 18–34 **(17 pages).**

Andres, L.; Boateng, K.; Borja-Vega, C.; Thomas, E., (2018). A review of in-situ and remote sensing technologies to monitor water and sanitation interventions. Water. 10: 756 **(13pages).**

Androniceanu, A.; Sabie, O.M., (2022). Overview of green energy as a real strategic option for sustainable development. Energies. 15: 8573 **(35 pages).**

Aprianto, A.; Maulana, A.; Noviandy, T.R.; Lala, A.; Yusuf, M.; Marwan, M.; Perucha, R.; Afidh, F.; Irvanizam, I.; Nizamuddin, N.; Idroes, G.M., (2023). Exploring geothermal manifestations in Ie Jue, Indonesia: Enhancing safety with unmanned aerial vehicle. Leuser J. Environ. Stud., 1: 2023 **(8 pages).**

Azarpour, A.; Mohammadzadeh, O.; Rezaei, N.; Zendehboudi, S., (2022). Current status and future prospects of renewable and sustainable energy in north America: Progress and challenges. Energy Convers. Manage. 269: 115945 **(37 pages).**

Azhar, F.; Misbullah, A.; Lala, A.; Idroes, G.M.; Kusumo, F.; Noviandy, T.R.; Irvanizam, I.; Idroes, R., (2024). Evaluating geothermal power plant sites with additive ratio assessment: Case study of Mount Seulawah Agam, Indonesia. Heca J. Appl. Sci., 2: 19–26. **(8 pages).**

Bahri, R.A.; Noviandy, T.R.; Suhendra, R.; Idroes, G.M.; Yanis, M.; Yandri, E.; Nizamuddin, N.; Irvanizam, I., (2023). Utilization of drone with thermal camera in mapping digital elevation model for Ie Seu'um geothermal manifestation exploration security. Leuser J. Environ. Stud. 1: 25–33 **(9 pages).**

Bhagaloo, K.; Ali, R.; Baboolal, A.; Ward, K., (2022). Powering the sustainable transition with geothermal energy: A case study on Dominica. Sustainable Energy Technol. Assess., 51: 101910 **(14 pages).**

BSN, (2004). Air dan air limbah–Bagian 8: Cara uji timbal (Pb) dengan Spektrofotometri Serapan Atom (SSA)-Nyala. SNI 06-6989.8-2004 **(1 page).**

Christian, G.D.; Dasgupta, P.K.; Schug, K.A., (2013). Analytical chemistry. John Wiley and Sons. **(850 pages).**

Darma, S., (2016). Indonesia, in: Geothermal power generation. Elsevier. 609–643 **(35 pages).**

de Jesus, A.C., (2016). Environmental benefits and challenges associated with geothermal power generation, in: Geothermal power generation: Dev. innovation. Elsevier Inc. 477–498 **(22 pages).**

Gutiérrez-Negrín, L.C.A., (2024). Evolution of worldwide geothermal power 2020–2023. Geotherm. Energy. 12: 14 **(60 pages).**

Hardi, I.; Idroes, G.M.; Hamaguchi, Y.; Can, M.; Noviandy, T.R.; Idroes, R., (2024). Business confidence in the shift to renewable energy: A country-specific assessment in major Asian economies. J. Econ. Technol., **(38 pages).**

Hossain, M.; Karmakar, D.; Begum, S.N.; Ali, S.Y.; Patra, P.K., (2021). Recent trends in the analysis of trace elements in the field of environmental research: A review. Microchem. J., 165: 106086 **(18 pages).**

Idroes, Ghalieb Mutig.; Hardi, I.; Hilal, I.S.; Utami, R.T.; Noviandy, T.R.; Idroes, R., (2024a). Economic growth and environmental impact: Assessing the role of geothermal energy in developing and developed countries. Innov. Green Dev., 3: 100144 **(12 pages).**

Idroes, Ghalieb Mutig.; Hardi, I.; Rahman, M.H.; Afjal, M.; Noviandy, T.R.; Idroes, R., (2024b). The dynamic impact of non-renewable and renewable energy on carbon dioxide emissions and ecological footprint in Indonesia. Carbon Res., 3: 35 **(21 pages).**

Idroes, Ghazi Mauer.; Suhendrayatna, S.; Khairan, K.; Suhartono, E.; Prasetio, R.; Riza, M., (2024). Ensuring accuracy: Critical validation techniques in geochemical analysis for sustainable geothermal energy development. Leuser J. Environ. Stud. 2: 19–29 **(11 pages).**

Idroes, R.; Marwan, M.; Yusuf, M.; Muslem, M.; Helwani, Z., (2021). Geochemical investigation on Jaboi manifestation, Jaboi Volcano, Sabang, Indonesia. Int. J. Geomate., 20: 170–185 **(16 pages).**

Idroes, R.; Yusuf, M.; Saiful, S.; Alatas, M.; Subhan, S.; Lala, A.; Muslem, M.; Suhendra, R.; Idroes, G.M.; Marwan, M.; Mahlia, T.M.I., (2019). Geochemistry exploration and geothermometry application in the North Zone of Seulawah Agam, Aceh Besar District, Indonesia. Energies. 12: **(17 pages).**

Islam, M.T.; Nabi, M.N.; Arefin, M.A.; Mostakim, K.; Rashid, F.; Hassan, N.M.S.; Rahman, S.M.A.; McIntosh, S.; Mullins, B.J.; Muyeen, S.M., (2022). Trends and prospects of geothermal energy as an alternative source of power: A comprehensive review. Heliyon. 8: e11836 **(17 pages).**

Kassim, N.S.A.; A. I. S. M. Ghazali, S.; Liyana Bohari, F.; A. Z. Abidin, N., (2022). Assessment of heavy metals in wastewater plant effluent and lake water by using atomic absorption spectrophotometry. Mater. Today Proc. 66: 3961–3964 **(4 pages).**

Kementerian Kesehatan, (2017). Peraturan Menteri Kesehatan Republik Indonesia Nomor 32 Tahun 2017 **(31 pages).**

Kementerian Kesehatan, (2010). Peraturan Menteri Kesehatan Republik Indonesia Nomor 492/MENKES/PER/IV/2010 **(9 pages).**

Kumar, L.; Hossain, M.S.; Assad, M.E.H.; Manoo, M.U., (2022). Technological advancements and challenges of geothermal energy systems: a comprehensive review. Energies. 15: 9058 **(18 pages).**

Lala, A.; Yusuf, M.; Suhendra, R.; Maulydia, N.B.; Dharma, D.B.; Saiful, S.; Idroes, R., (2024). Characterization of geochemical and isotopic profiles in the Southern Zone geothermal systems of Mount Seulawah Agam, Aceh Province, Indonesia. Leuser J. Environ. Stud. 2: 30–40 **(11 pages).**

Letcher, T.M., (2022). Global warming, greenhouse gases, renewable energy, and storing energy, in: Storing Energy. Elsevier. 3–12 **(10 pages).**

Lin, X.-M.; Kireeva, N.; Timoshin, A.V.; Naderipour, A.; Abdul-Malek, Z.; Kamyab, H., (2021). A multi-criteria framework for designing of stand-alone and grid-connected photovoltaic, wind, battery clean energy system considering reliability and economic assessment. Energy. 224: 120154 **(15 pages).**

Lund, J.W.; Huttrer, G.W.; Toth, A.N., (2022). Characteristics and trends in geothermal development and use, 1995 to 2020. Geothermics., 105: 102522 **(10 pages).**

Lund, J.W.; Toth, A.N., (2021). Direct utilization of geothermal energy 2020 worldwide review. Geothermics., 90 **(31 pages).**

Marwan, Isa, M.; Idroes, R.; Nursyafira, Idris, S.; Yanis, M.; Ghani, A.A.; Paembonan, A.Y., (2023). Geoelectrical model of geothermal spring in ie jue seulawah deriving from 2d vlf-em and dc resistivity methods. J. Appl. Eng. Sci., 21: 59–69 **(11 pages).**

Marwan, Syukri, M.; Idroes, R.; Ismail, N., (2019). Deep and shallow structures of geothermal Seulawah Agam based on electromagnetic and magnetic data. Int. J. Geomate. 16: 141–147 **(7 pages).**

Maulidar, P.; Fadila, S.; Hafizah, I.; Zikra, N.; Idroes, G.M., (2024). Enhancing environmental quality: Investigating the impact of hydropower energy consumption on CO_2 emissions in Indonesia. Ekonomikalia J. Econ., 2: 53–65 **(13 pages).**

Maulydia, N.B.; Idroes, R.; Khairan, K.; Tallei, T.E.; Mohd Fauzi, F., (2024a). Ecotoxicological insight of phytochemicals, toxicological informatics, and heavy metal concentration in Tridax procumbens L. in geothermal areas. Global J. Environ. Sci. Manage., 10: 369–384 **(16 pages).**

Maulydia, N.B.; Khairan, K.; Tallei, T.E.; Mohd Fauzi, F.; Idroes, R., (2024b). Analysis of geothermal impact on metabolite compounds of heat-tolerant plant species using clustering and similarity cliff. Global J. Environ. Sci. Manage., 10: 1827–1842 **(16 pages).**

McCleskey, R.B.; Cravotta, C.A.; Miller, M.P.; Tillman, F.; Stackelberg, P.; Knierim, K.J.; Wise, D.R., (2023). Salinity and total dissolved solids measurements for natural waters: An overview and a new salinity method based on specific conductance and water type. Appl. Geochemistry. 154: 105684 **(13 pages).**

Meirbekova, R.; Bonciani, D.; Olafsson, D.I.; Korucan, A.; Derin-Güre, P.; Harcouët-Menou, V.; Bero, W., (2024). Opportunities and challenges of geothermal energy: A comparative analysis of three European Cases—Belgium, Iceland, and Italy. Energies. 17: 4134 **(27 pages).**

Miranda, M.M.; Raymond, J.; Dezayes, C., (2020). Uncertainty and risk evaluation of deep geothermal energy source for heat production and electricity generation in remote northern regions. Energies. 13: 4221 **(35 pages).**

Owebor, K.; Diemuodeke, E.O.; Briggs, T.A.; Imran, M., (2021). Power situation and renewable energy potentials in Nigeria – A case for integrated multi-generation technology. Renew. Energy. 177: 773–796 **(24 pages).**

Paepae, T.; Bokoro, P.; Kyamakya, K., (2021). From fully physical to virtual sensing for water quality assessment: A comprehensive review of the relevant state-of-the-art. Sensors. 21: 6971 **(35 pages).**

Pambudi, N.A., (2018). Geothermal power generation in Indonesia, a country within the ring of fire: Current status, future development and policy. Renew. Sustainable Energy Rev., 81: 2893–2901 **(9 pages).**

Pambudi, N.A.; Ulfa, D.K., (2024). The geothermal energy landscape in Indonesia: A comprehensive 2023 update on power generation, policies, risks, phase and the role of education. Renew. Sustainable. Energy Rev., 189: 114008 **(17 pages).**

Rahman, I.F.; Misbullah, A.; Irvanizam, I.; Yusuf, M.; Maulana, A.; Marwan, M.; Dharma, D.B.; Idroes, R., (2024). Optimizing geothermal power plant locations in Indonesia: A multi-objective optimization on the basis of ratio analysis approach. Infolitika J. Data Sci., 2: 1–8. **(8 pages).**

Rotich, I.K.; Chepkirui, H.; Musyimi, P.K.; Kipruto, G., (2024). Geothermal energy in Kenya: Evaluating health impacts and environmental challenges. Energy Sustainable Dev., 82: 101522 **(9 pages).**

Santos, L.; Dahi Taleghani, A.; Elsworth, D., (2022). Repurposing abandoned wells for geothermal energy: Current status and future prospects. Renew. Energy. 194: 1288–1302 **(15 pages).**

Sayed, E.T.; Wilberforce, T.; Elsaid, K.; Rabaia, M.K.H.; Abdelkareem, M.A.; Chae, K.-J.; Olabi, A.G., (2021). A critical review on environmental impacts of renewable energy systems and mitigation strategies: Wind, hydro, biomass and geothermal. Sci. Total Environ., 766: 144505 **(15 pages).**

Shah, M.; Prajapati, M.; Yadav, K.; Sircar, A., (2024). A comprehensive review of geothermal energy storage: Methods and applications. J. Energy Storage. 98: 113019 **(10 pages).**

Sharmin, T.; Khan, N.R.; Akram, M.S.; Ehsan, M.M., (2023). A state-of-the-art review on geothermal energy extraction, utilization, and improvement strategies: Conventional, hybridized, and enhanced geothermal systems. Int. J. Thermofluids. 18: 100323 **(25 pages).**

Soltani, M.; Moradi Kashkooli, F.; Souri, M.; Rafiei, B.; Jabarifar, M.; Gharali, K.; Nathwani, J.S., (2021). Environmental, economic, and social impacts of geothermal energy systems. Renew. Sustainable Energy Rev. 140: 110750 **(25 pages).**

Zhang, Q.; Chen, S.; Tan, Z.; Zhang, T.; Mclellan, B., (2019). Investment strategy of hydrothermal geothermal heating in China under policy, technology and geology uncertainties. J. Clean. Prod. 207: 17–29 **(13 pages).**

AUTHOR (S) BIOSKETCHES

Idroes, G.M., Ph.D., Candidate, Graduate School of Mathematics and Applied Sciences, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia.
- Email: *idroesghazi@gmail.com*
- ORCID: 0000-0001-6217-9067
- Web of Science ResearcherID: HSI-2075-2023
- Scopus Author ID: 57201859084
- Homepage: https://usk.ac.id/

Rezeki, D.P., B.Sc., Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *deaputrii12razekii@gmail.com*
- ORCID: 0009-0007-1837-4464
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://usk.ac.id/

Khairi, K., Ph.D., Associate Professor, Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *khairi@usk.ac.id*
- ORCID: 0000-0001-5366-4423
- Web of Science ResearcherID: NA
- Scopus Author ID: 56524475200
- Homepage: https://fsd.usk.ac.id/khairi/

Khairan, K., Ph.D., Associate Professor, Department of Pharmacy, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *khairankhairan@usk.ac.id*
- ORCID: 0000-0003-3028-6022
- Web of Science ResearcherID: GPS-9955-2022
- Scopus Author ID: 37016941000
- Homepage: https://fsd.usk.ac.id/kkh/

Idroes, R., Ph.D., Professor, Department of Pharmacy, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
- Email: *rinaldi.idroes@usk.ac.id*
- ORCID: 0000-0003-2264-6358
- Web of Science ResearcherID: S-8983-2016
- Scopus Author ID: 57192873366
- Homepage: https://fsd.usk.ac.id/rinaldi.idroes/

Suhartono, E., Ph.D. Professor, Department of Medical Chemistry/Biochemistry, Faculty of Medicine, Lambung Mangkurat University, Banjarbaru 70124, Indonesia
- Email: *ekoantioxidant@gmail.com*
- ORCID: 0000-0002-1239-6335
- Web of Science ResearcherID: AAG-9351-2019
- Scopus Author ID: 56951281500
- Homepage: https://brin.go.id/

AUTHOR (S) BIOSKETCHES

Prasetio, R., Ph.D. Researcher, Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
▪ Email: *rasi.prasetio@brin.go.id*
▪ ORCID: 0000-0002-6682-653X
▪ Web of Science ResearcherID: LJL-3979-2024
▪ Scopus Author ID: 55352219500
▪ Homepage: https://ulm.ac.id/

Rahman, S.A., Ph.D., Associate Professor, Faculty of Chemical & Process Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Persiaran Tun Khalil Yaakob, 26300 Gambang, Kuantan, Pahang, Malaysia.
▪ Email: *sunarti@ump.edu.my*
▪ ORCID: 0000-0003-0986-5548
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57218826247
▪ Homepage: https://www.umpsa.edu.my/en

Suhendrayatna, S., Ph.D., Professor, Department of Chemical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.
▪ Email: *suhendrayatna@usk.ac.id*
▪ ORCID: 0000-0002-2673-0947
▪ Web of Science ResearcherID: I-7750-2017
▪ Scopus Author ID: 7409901056
▪ Homepage: https://fsd.usk.ac.id/suhendrayatna/

HOW TO CITE THIS ARTICLE

Idroes, G.M.; Rezeki, D.P.; Khairi, K.; Khairan, K.; Idroes, R.; Suhartono, E.; Prasetio, R.; Rahman, S.A.; Suhendrayatna, S., (2024). Validation of heavy metals in geothermal to support water management practices and mitigation strategies. Global J. Environ. Sci. Manage., 10(SI): 153-166.

DOI: 10.22034/gjesm.2024.10.SI.10

URL: https://doi.org/10.22034/GJESM.2024.SI.10

Global J. Environ. Sci. Manage. 10(SI): 167-180, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Food waste reduction strategies in composting and recycling centers based on material flow analysis

S.C. Zahra[1], A.D. Anggrainy[2], Z. Mohd-Zaki[3], A.Y. Bagastyo[1,*]

[1] *Department of Environmental Engineering, Faculty of Civil Engineering, Planning, and Geo-Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia*

[2] *Research Center for Infrastructure and Sustainable Environment, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia*

[3] *Civil Engineering Studies, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Permatang Pauh Campus, 13500 Pulau Pinang, Malaysia*

ARTICLE INFO

Article History:
Received 22 May 2024
Revised 29 July 2024
Accepted 05 September 2024

Keywords:
Black soldier fly (BSF)
Composting
Food waste
Material flow analysis
Waste recycling
Waste reduction

ABSTRACT

BACKGROUND AND OBJECTIVES: Food waste has major environmental, economic, and social impacts, contributing to greenhouse gas emissions, soil depletion, global food insecurity, and rising food prices. Addressing the global challenge of food waste necessitates a heightened focus on food waste treatment. This investigation analyzed the extent of food waste reduction achieved at composting and recycling centers in Surabaya. The objective of this study is to evaluate the effectiveness of food waste reduction at composting and recycling facilities.
METHODS: The study utilized material flow analysis to assess food waste reduction at the Wonorejo composting and the Jambangan recycling centers. The present analysis examines the quantity and dynamics of food waste, starting with i) the pre-treatment stage that encompasses sorting, shredding, and sieving; ii) the composting process, which involves the generation of compost and the loss of water; and finally, iii) the bioconversion process facilitated by black soldier fly larvae, highlighting the production of larvae biomass and frass.
FINDINGS: At the Wonorejo composting and Jambangan recycling centers, composting served as the main approach for the treatment of food waste. At the Wonorejo composting center, over 99 percent of food waste was composted, whereas 0.22 percent was managed through black soldier fly larvae bioconversion. Within this composting center, the conversion rates revealed that 70.71 percent of the food waste was processed into mature compost. Furthermore, 0.03 percent was utilized for larval biomass production, 24.94 percent was lost to moisture, and 4.32 percent remained as residual waste. At the Jambangan recycling center, 85.74 percent of food waste was composted, whereas the remaining 14.26 percent was handled through black soldier fly larva bioconversion. Approximately 40.03 percent was transformed into mature compost, 1.37 percent into larval biomass, 29.26 percent lost as moisture, and the remaining 29.34 percent was landfilled.
CONCLUSION: Material flow analysis revealed that compost and recycling center facilities preferred composting over black soldier fly larva bioconversion for food waste reduction. Composting proved to be an effective method for processing over 85 to 99 percent of food waste, while the application of black soldier fly larvae bioconversion resulted in a mere 0.2 to 14 percent of food waste being treated. In light of the significant volume of food waste that continues to be disposed of in landfills, it is imperative for the Surabaya City Government to establish additional composting facilities in various locations. Furthermore, the implementation of supplementary strategies, including the management of surplus food distribution and the encouragement of composting at the household level, is essential for enhancing food waste management throughout the supply chains.

DOI: 10.22034/gjesm.2024.10.SI.11

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
39	6	2

*Corresponding Author:
Email: *bagastyo@enviro.its.ac.id*
Phone: +62812 2225 7893
ORCID: 0000-0001-8850-9255

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Food waste (FW) includes discarded, wasted, spoiled, or decomposed food that occurs in the final stages of the food supply network (i.e., distribution, market retail, and consumption) (Kavitha *et al*., 2020). Annually, 1.6 billion tons of food—one-third of worldwide food production—are wasted. This amount is estimated to rise to 2.1 billion tons by 2030 (Hegnsholt *et al*., 2018). Conversely, in 2022, between 691 and 783 million individuals globally faced starvation or malnutrition as a result of inadequate or constrained food resources (WHO, 2023). This situation highlights that the global increase in FW corresponds to significant economic losses and highly inefficient use of resources (FAO, 2024). Both industrialized and developing nations may experience increases in WF resources, though the magnitude of such increases can vary significantly due to factors including income disparities, levels of urbanization, and the pace of economic growth (Chalak *et al*., 2016). Therefore, prioritizing FW prevention and reduction is critical to optimizing resources use, ensuring food security (FAO, 2022), and reducing hidden impacts such as climate change, eutrophication, water depletion, agricultural land occupation, land transformation fossil depletion, terrestrial acidification, photochemical oxidant and particulate production, and adverse health effects to humans (Skaf *et al*., 2021). As a developing nation with a population exceeding 260 million, Indonesia has experienced analogous issues. In 2023, FW accounted for 41.7 percent (%) of the total solid waste generation (MEFRI, 2024). From 2000 to 2019, Indonesia's food loss and waste (FLW) generation reached 23–48 million tons annually (MNDPRI, 2021). An increase of approximately 15% in the generation of FW was identified during the distribution and consumption processes, with the consumption phase accounting for the largest share, estimated between 5 and 19 million tons per year. The economic loss caused by food loss and waste are estimated to be between 213 trillion and 551 trillion rupiahs per year (4–5% of Indonesia's Gross Domestic Product). Surabaya alone generated FW of approximately 0.37 million tons per year (t/y) (MEFRI, 2024). In order to tackle the problem of FW and reduce the volume of organic waste directed to landfills, the Surabaya City Government routinely implements food and organic waste management strategies at composting facilities, recycling centers, and gasification systems located in proximity to landfill sites. Surabaya has 24 compost centers and 2 recycling center facilities. Between 2021–2023, the average amount of solid waste processed by composting centers was 32101.19 tons, while recycling centers handled 9105.39 t/y (MEFRI, 2024). Composting was the primary waste treatment in these facilities. the bioconversion process utilizing black soldier fly larvae (BSFL) was introduced whitin facilities dedicated to recycling and composting. The introduction of this new method changes the ratio of solid waste treatment in composting and recycling center facilities from 100% composting (by 2021) to 80:20 composting: BSFL (by 2022) and 76:24 composting: BSFL (by 2023). Composting has been recognized as an effective approach to waste treatment (Lai *et al*., 2024). The degradation of organic materials by microorganisms occurs in regulated environments, including moisture content, carbon-to-nitrogen (C/N) ratio, temperature, potential of hydrogen (pH), oxygen, and particle size, to produce reasonably stable compost that is pathogen-free and can be beneficially applied as a soil fertilizer. Throughout the composting process, it was necessary to either manually or mechanically mix the composting materials to ensure the introduction of oxygen and fresh air. Additionally, water was periodically introduced to sustain an optimal moisture level the compost pile. Microorganisms generate heat during active composting, releasing carbon dioxide (CO_2) and moisture into the atmosphere (Oshins *et al*., 2022). Conversely, the black soldier fly (*Hermetia illucens*) has been widely renowned for its efficacy in waste valorization. Many studies have found that BSFL can convert FW (Fadhillah and Bagastyo, 2020; Kim *et al*., 2021), human feces (Gold *et al*., 2020), animal manure (Lalander *et al*., 2019), and other types of organic waste (Gao *et al*., 2019; Raksasat *et al*., 2022) into body mass. BSFL is rich in fat and protein and can partly replace traditional animal feedstuff or be used for biofuel production (Barragan-Fonseca *et al*., 2017). Moreover, BSFL bioconversion can be completed in two weeks (Song *et al*., 2021), faster

than aerobic composting. Several studies have utilized material flow analysis (MFA) to assess, simulate, and investigate the movement of municipal solid waste (MSW). In Indonesia, this analysis has only been done in Bali Province (54.06% of total MSW was properly managed) (Widyarsana *et al.,* 2020), and rural cities like Batang (with 49.32% waste reduction) (Budihardjo *et al.,* 2023) and Klaten (up to 85% waste reduction was simulated) (Ratnawati *et al*., 2023). There is a notable deficiency in studies focused on the reduction of FW. Furthermore, the use of material flow analysis in examining particular FW streams remains underexplored.. Surabaya, the second largest city in Indonesia, is a metropolis with approximately 3 million inhabitants. It has a high generation of FW (57.03% of the total MSW), which has the potential to be analyzed. A material flow analysis was executed in this case study to assess the trajectory and amount of FW processed in the waste treatment facilities located in Surabaya. The study aims to analyze the effectiveness of FW treatment employed in the largest composting and recycling facilities. FW management was also evaluated to develop strategies to tackle FW problems. This study was carried out in Surabaya, Indonesia, in 2023.

MATERIALS AND METHODS

Study area

Surabaya, located at 7°14'57.01" South latitude and 112°45'2.99" East longitude, is covered by a total area of 335.93 square kilograms (km^2) and is characterized by a tropical climate with an average temperature ranging from 27.4 to 30.7 degrees Celsius (°C). This study focuses on two of the largest waste treatment facilities in Surabaya, specifically the Wonorejo composting center and the Jambangan recycling center, which have been chosen as the primary study sites (Fig. 1). In 2022, the Wonorejo composting center received approximately 9288.16 t/y of solid waste, while the Jambangan recycling center processed about 2268.08 t/y (MEFRI, 2024). The Wonorejo composting center obtains FW from the Keputran traditional market, the Sutorejo recycling center, and the nearby culinary center. Conversely, the Jambangan recycling facility receives mixed solid waste sourced from local households, traditional markets, and the catering sector, and it separates FW from two community organizations.

FW treatment

The FW treatment scheme at the Wonorejo composting and Jambangan recycling centers is illustrated in Fig. 2. Although the Wonorejo composting and Jambangan recycling centers implement similar FW treatment methods, the proportion of FW treated by composting and BSFL bioconversion was quite different. The Wonorejo composting facility employs a composting method for food waste derived from the Keputran traditional markets and the Sutorejo recycling centers, whereas the bioconversion of FW using BSFL is exclusively applied to the FW from the culinary center. Likewise, the Jambangan recycling center uses composts FW from households, traditional markets, and the catering industry. The application of BSFL bioconversion was utilized for merely a small proportion of predominantly that obtained.

Data collection and composition analysis

Over the course of eight consecutive days, primary data were gathered to evaluate the amount and characteristics of waste entering the two facilities. The FW from each source was directly sorted into 10 categories (i.e., fruits, vegetables, fish and seafood, meat, legumes, bakery products, dairy products, dried foods, mixed foods, and others) and then weighed. The calculation of FW for each category can be done using Eq. 1 (Zakarya *et al.,* 2021):

$$Food\ \ waste\ per\ category = \frac{\sum_{i=1}^{n} Xi}{\sum_{i=1}^{n} Yi} \times 100\% \quad (1)$$

Xi refers to the weight of each category of FW in kilogram(kg), and *Yi* is the total weight of FW in each waste treatment facility (kg).

Mass balance analysis

On days 10 and 40 of the treatment, further primary data were collected following the execution of the BSFL bioconversion and composting processes. The weights of various products, such as BSFL frass, larvae biomass, compost, and residue, were assessed to calculate the percentage of FW reduction in both facilities, utilizing Eqs. 2 and 3



Fig. 1: Geographic location of the study area in Surabaya (Wonorejo composting center) the Jambangan recycling center) in Indonesia

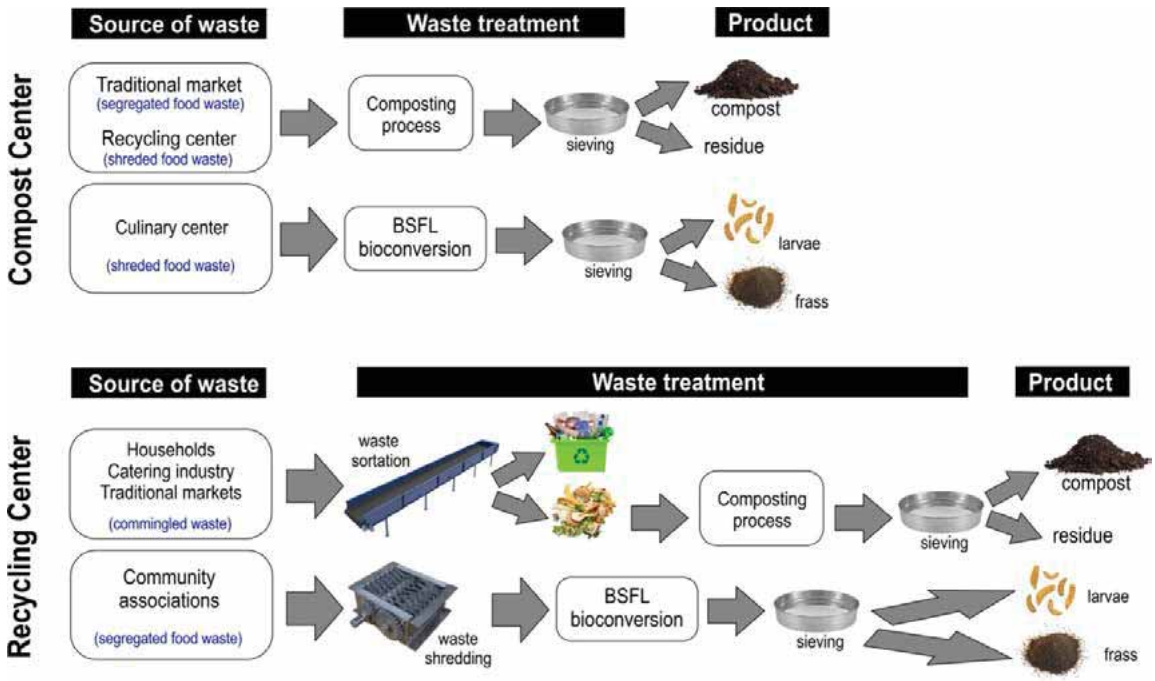


Fig. 2: General waste treatment scheme at the (a) Wonorejo composting center and (b) Jambangan recycling center

Table 1: Average quantity of waste in composting and recycling centers

Waste management facilities	Waste characteristics	Source of waste	Average waste quantity	
			(kg/d)	(%)
Wonorejo composting center	100% segregated	The traditional Keputran market	6476.25	84.65
		Sutorejo recycling center	1158.12	15.14
		Culinary centers	16.51	0.22
Jambangan recycling center	94.82% were commingled, 5.18% were segregated	Households	337.56	40.63
		Catering industry	322.50	38.82
		Traditional markets	127.60	15.36
		Community associations	43.10	5.18

(Zahra, 2023):

$$Mass\ of\ FW_{in\ ending\ time\ of\ the\ periode} = Mass\ of\ FW_{in\ a\ given\ period} - Mass\ of\ FW_{in\ a\ beginning\ time\ of\ period} \quad (2)$$

$$\%\ FW_{reduction} = \frac{Mass\ of\ FW_{in\ ending\ time\ of\ period}}{Mass\ of\ FW_{in\ a\ beginning\ time\ of\ period}} \times 100 \quad (3)$$

Material flow analysis

The MFA of FW was conducted using STAN 2.7.101 (substance flow analysis software, Technische Universität Wien). MFA is a generally used methodical analysis of a given system's material and stock movements at a particular moment and location (Brunner and Rechberger, 2016). This technique is often employed to facilitate policy-making processes in the domains of waste, resource, and environmental management. The results of the MFA can be verified through material balance by comparing material flows, including input, pathway, intermediates, and output generation.

RESULTS AND DISCUSSION

Solid waste quantity and composition

On average, the Wonorejo composting center

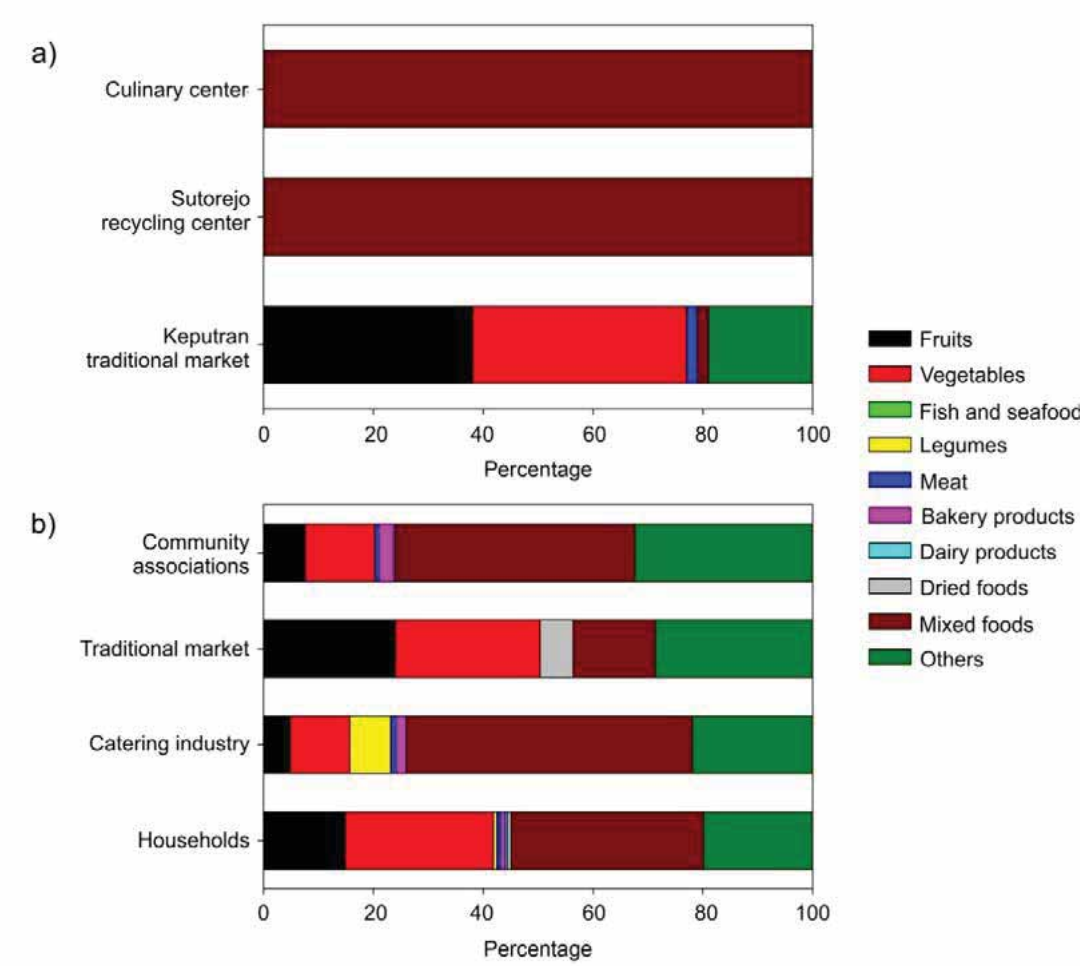


Fig. 3: Average composition of FW obtained from the (a) Wonorejo composting center and (b) Jambangan recycling center

received FW with a quantity of 7,650.89 kilogram per day (kg/d), while the Jambangan recycling center received 830.72 kg/d of MSW (Table 1). It is estimated that approximately 84% of the FW received by the Wonorejo composting center was sourced from the Keputran traditional market. The largest proportion of FW from the Keputran traditional market was fruits and vegetables (~38% each), whereas mixed foods, meat and dried foods accounted for up to 2% of the total FW (Fig. 3a). At the Sutorejo recycling and culinary center, the waste stream was exclusively made up of mixed waste. In the Jambangan recycling center, around 94% of the municipal solid waste was similarly categorized as mixed waste, while a mere 5% from the community association was fully separated. After sorting, the ratio of FW to recycled waste was 1:2. Waste from households, the catering industry, and the traditional market was predominantly mixed food (34.05% on average) (Fig. 3b). The waste generated by community associations was comprised of 43.70% mixed food items, 12.66% vegetables, and 7.61% fruits. In comparison to a different recycling facility, the organic waste composition at the Jambangan recycling center was found to be 8% lower than that recorded at the Batu recycling center in Indonesia (Muktiningsih *et al.*, 2023).

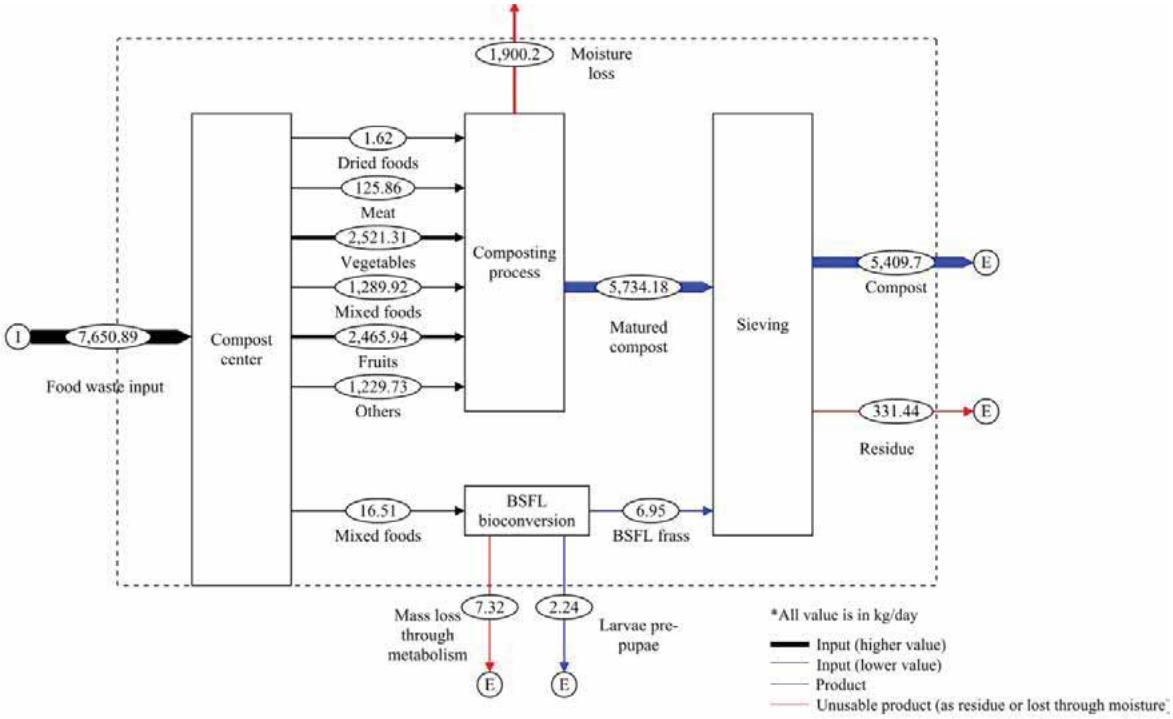


Fig. 4: MFA of the FW at the Wonorejo composting center

MFA in the Wonorejo composting center

The material flow of FW in the Wonorejo composting center is shown in Fig. 4. The composting process effectively treated more than 99% of the total food waste, which equated to 7634.38 kg per day, over a period of roughly 40 days. This process facilitated the transformation of approximately 74% of the food waste, specifically 5734.18 kg per day into mature compost. FW from the culinary center, which accounted for 0.22% of total FW, was treated using BSFL bioconversion for approximately 10 days. This process converts 0.03% FW into larval biomass and 0.09% FW into BSFL frass. BSFL frass has a compost-like structure and consists of mixtures of excrement, feeding materials, part of larval biomass, dead eggs, and substances from dead larvae (EU, 2021). The frass generated by BSFL shares characteristics with compost, exhibiting a high concentration of dry organic material and being rich in nutrients, chitin, and microorganisms that facilitate the uptake of nutrients by plants (Setti *et al*., 2019). The application of BSFL frass in its raw form is discouraged due to its immature and biologically unstable nature, which may harbor phytotoxins detrimental to plant growth (Basri *et al*., 2022; Elissen *et al*., 2023).

Considering the small amount of BSFL frass produced, mature compost and BSFL frass were mixed and sieved together. Overall, the FW reduction at this center reached 95.67%, leaving 4.33% (331.44 kg/d) of FW as residue that goes into landfills.

MFA at the Jambangan recycling center

The material flow of solid waste in the Jambangan recycling center is illustrated in Fig. 5. On average, the Jambangan recycling center received 830.73 kg/d of solid waste. After the segregation process, the amount of recyclable waste that could be recovered was 528.67 kg (63.64% of the total solid waste), while the amount of FW that required treatment was 302.06 kg (36.36%). It is estimated that around 85.74% of the total FW was processed via composting techniques. Moisture loss accounted for approximately 21.34% of the total FW, leaving 64.40%—or 194.52 kg—effectively converted into

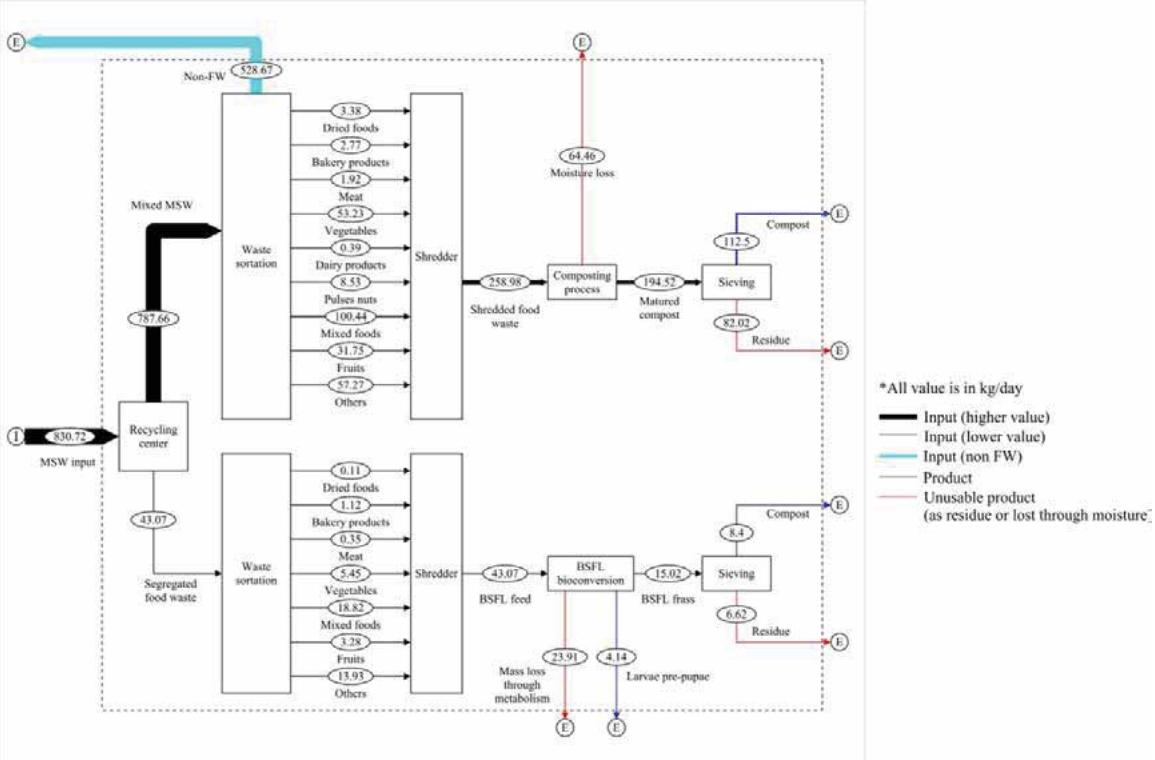


Fig. 5: MFA of the FW at the Jambangan recycling center

mature compost. After sieving, the residue from the composting process amounted to 82.02 kg (27.15%).

In contrast, only ~14% of the total FW was treated using BSFL bioconversion. This portion of FW was entirely contributed by the community association. The segregation process was unnecessary since the FW) had already been pre-sorted. The bioconversion of FW by BSFL resulted in the transformation of roughly 1% of the FW into larval biomass, while less than 5% was converted into BSFL frass. Overall, the FW reduction achieved through composting and BSFL bioconversion was 70.65%.

Evaluation of composting and recycling centers for FW reduction

The findings from the material flow analysis conducted on the facilities for composting and recycling indicated that the composting center demonstrated a greater efficacy in minimizing FW. However, its effectiveness may not be sufficient to address the quantity of FW generated in Surabaya. Data from the Information System of National Waste Management (MEFRI, 2024) revealed that the amount of Surabaya MSW sent to composting and recycling centers in 2023 was only 32,998 and 63,569 t/y, respectively (representing 1–5% of the total MSW). If all compost centers were assumed to accept 100% FW, their combine capacity would still be only 8% of the total FW generation in the city. It is improbable that this is the case, as the compost center also processes organic waste generated from the trimming of street trees. Several studies have also conducted modeled material flow analyses of MSW. It was revealed that 20.13 t/y of MSW generated at boarding schools in Bogor, Indonesia, could be processed through composting and black soldier fly (BSF) maggot cultivation, resulting in 33% compost and 67% maggot production (Rimantho *et al.*, 2022). In Klaten Regency, approximately 26.39 tons/day (t/d) of compost could be simulated from 37.7 t/d of MSW (Ratnawati *et al.*, 2023). The findings of these studies indicate that both the waste treatment conditions and the volume of input materials have a substantial impact on the resulting



Fig. 6: Community compost bins (SES, 2020)

Table 2: Recommended strategies and practices for FW reduction

Stakeholders	Strategies and practices	Remarks
Households	Preparing for grocery shopping	The grocery shopping list is beneficial for reducing food waste and saving money. Take a list of which groceries are needed and which are currently available at home.
	Finish the meal	Take enough food portions.
Households, retail, markets, hospitality and culinary industries, etc.	Encourage good handling practices in food management	Proper food management can prevent food spoilage and reduce the number of leftovers. It is also useful to guarantee the safety, quality, and integrity of food.
	Donate surplus food to those in need	According to the Food and Agriculture Organization, approximately 17% of the total food that was accessible in 2019 was wasted by households, retailers, restaurants, and other similar food-related businesses (UNEP, 2021). Surplus food donation effectively relieves food insecurity, reduces FW, and decreases carbon emissions (Sundin *et al*., 2022).
Government	Create an online platform to assist in the distribution of excess food.	This platform connects shops, restaurants, caterers, hotels, etc., that have surplus food to communities in need.
	Add several composting centers that are 100% dedicated to FW treatment.	The added composting center added could increase the amount of FW that can be treated. A composting center located near a market could also be necessary to facilitate waste transport.
	Encourage households and communities to manage regional-scale composting and BSFL processing units (Farahdiba *et al*., 2023).	An on-site composting system and BSFL processing units can ensure direct FW treatment. Additionally, it decreases the need for transportation and waste storage infrastructure while reducing leachate. Ensuring proper waste collection, hygienic segregation, and employing skilled operators and laborers are essential to prevent contamination and odor, ensuring effective treatment and long-term sustainability of facilities.

products. Another study suggested that the utilization of landfills could be reduced by enhancing the percentage of waste that undergoes treatment (Thushari *et al.,* 2020). Raising the composting rate from 5.4% to 30% and the incineration rate from 2% to 30% could reduce the MSW amount sent to landfills by 63%.

Evaluation of Surabaya's MSW management

Surabaya's waste management follows the basic framework of the National MSW Management Policy and Strategy, as outlined in Presidential Regulation No. 97/2017 (Tetra Tech, 2021). The goal is to implement a fully effective solid waste management system in urban settings by advocating for the 3Rs (Reduce, Reuse, Recycle) and ensuring proper management of residential waste by 2025. Additionally, under the National Medium-Term Development Plan for 2020–2024, Indonesia aims to decrease 30% of solid waste via the implementation of the 3Rs and achieve a 70% reduction through sorting, collection, transportation, treatment, and disposal processes (Tetra Tech, 2021). The implementation of these frameworks aims to promote the practices of reusing and recycling household waste, as well as composting organic materials among residents. As of 2020, there were around 5,267 community compost bins distributed across Surabaya City (Fig. 6) (SES, 2020). However, a recent study (Bappedalitbang, 2022) showed that FW reduction is still far from meeting target goals. In the year 2021, a total of 2,720.14 tons of waste were produced, with organic waste constituting 55% of this total. The overall waste reduction achieved was merely 50.92%, which included a reduction of 4.18% attributed to recycling, composting, and BSFL bioconversion, alongside a significant 46.11% reduction resulting from gasification processes.

Meanwhile, in 2023, although the amount of MSW sent to landfill was reduced by 5% (from 1,700 to 1600 tons/day), 60% of the MSW was still composed by organic waste (SCG, 2023). This implies that the efforts to decrease food and other organic waste have not been fully effective. Consumer habits, such as a rise in the consumption of products and the practice of not finishing meals or having excess food, may also play a significant role in the considerable volume of FW generated in the city.

Suggestions and future directions for FW reduction

FW issues are significantly influenced by population growth, urbanization, economic growth, daily habits, and poor food management. FW will continue to increase unless a sustainable management approach is adopted. Therefore, several recommended strategies and practices must be implemented to address FW problems (Table 2).

CONCLUSION

The reduction of FW at the two largest Surabaya waste's treatment facilities was examined using material flow analysis based on waste input, segregation, transformation, and output. The Wonorejo composting facility processed an average of 7,650.89 kilograms of FW each day, whereas the Jambangan recycling center handled 830.72 kilograms of MSW on a daily basis. Approximately 84% of the FW generated in Wonorejo originates from the Keputran traditional market, with fruits and vegetables each representing about 38% of the overall waste. At the Jambangan recycling center, mixed waste made up about 94% of the MSW, with a 1:2 ratio of FW to recyclable materials. In Jambangan, mixed foods represented the most prevalent form of FW, making up 34.05% of the total. This situation highlights that the waste segregation process at the Jambangan recycling center necessitates more intensive effort than that required at Wonorejo. Overall, the waste treatment facilities are actively operated through the collaborative management of communities and the government. The application of organic waste management techniques, including BSFL bioconversion and composting, has yielded both social and environmental advantages, thereby advancing the principles of the 3Rs in support of a circular economy. The material flow analysis demonstrated that at the Wonorejo composting center, with over 99% of the total FW (7,634.38 kg/d) handled by composting, 74% of the FW successfully transformed into mature compost. The remaining 0.22% of FW treated using BSFL bioconversion was converted into larval biomass and BSFL frass at rates of 0.03% and 0.09%, respectively. In contrast, the Jambangan recycling center only converted >85%

of FW into mature compost (64.40%) and moisture (21.34%), whereas approximately 14% of FW was transformed into larval biomass (1%) and BSFL frass (<5%). Based on the waste input, it can be concluded that the composting center processed more FW than the recycling center. To summarize, composting centers demonstrate the potential to decrease more than 95% of FW, in contrast to recycling centers, which can only achieve a reduction of 70% in food waste. Despite the composting center's effectiveness in FW reduction and the government's strategy for treating FW, the overall FW reduction in Surabaya remains below optimal levels. This emphasizes the importance of increasing public understanding of communal composting initiatives within the Surabaya community. Data in 2023 showed that 60% of the landfilled MSW was still dominated by organic waste, creating opportunities for the upcycling process in the treatment centers and alarming the communities' awareness to participate in the waste reduction campaigns. The patterns of consumer behavior, including tendencies toward overconsumption and the frequent practice of leaving food unfinished, may exacerbate the issue of FW in urban environments. These observations underscore the critical need for initiatives focused on waste reduction and proper segregation, beginning at the household level. Other strategies that can be implemented include planning before grocery shopping, finishing meals, promoting good food handling practices, donating surplus food, creating an online platform for food distribution, establishing additional compost centers dedicated to food waste treatment, and encouraging households and communities to manage regional-scale composting and BSFL processing units. The implementation of these strategies generates enhanced economic value and creates employment opportunities within the region, thereby providing local governments with viable recommendations for addressing the challenges associated with waste management. Furthermore, the implementation of efficient waste collection systems, the hygienic separation of materials, and the engagement of trained personnel are crucial for achieving effective waste management and ensuring sustainability over the long term.

AUTHOR CONTRIBUTIONS

S.C. Zahra contributed to data analysis and manuscript preparation. A.D. Anggrainy contributed to data curation and manuscript preparation. Z. Mohd-Zaki contributed to manuscript's review and editing. A.Y. Bagastyo, the corresponding author, has contributed to supervising the first and second authors in the manuscript's data analysis, review, and editing.

ACKNOWLEDGEMENT

This study was performed in Surabaya, East Java, Indonesia, by a group from the Department of Environmental Engineering and Research Center for Infrastructure and Sustainable Environment, Institut Teknologi Sepuluh Nopember. The authors would like to acknowledge the Wonorejo and Jambangan waste treatment facilities as part of the study collaboration with the local authorities of Surabaya Environmental Services. The authors gratefully acknowledge financial support from the Institut Teknologi Sepuluh Nopember by the scheme of the Publication Writing and Intellectual Property Rights Incentive Program 2024.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the authors have fully observed ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

OPEN ACCESS

©2024 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
BSFL	Black soldier fly larvae
C/N	Carbon-to-nitrogen
CO_2	Carbon dioxide
Eq.	Equation
EU	European Union
FAO	Food and Agriculture Organization
Fig.	Figure
FLW	Food loss and waste
FW	Food waste
IFAD	International Fund for Agricultural Development
kg	Kilogram
kg/d	Kilogram per day
km^2	Square kilometer
MEFRI	Ministry of Environment and Forestry, the Republic of Indonesia
MFA	Material flow analysis
MNDPRI	Ministry of National Development Planning, the Republic of Indonesia
MSW	Municipal solid waste
pH	Potential of hydrogen
SCG	Surabaya City Government
SES	Surabaya Environmental Services
STAN	Substance flow analysis
t/d	Ton per day
t/y	Ton per year
UNEP	United Nation Environment Programme
UNICEF	United Nation Chlidren's Fund
WFP	World Food Programme
WHO	World Health Organization

REFERENCES

Bappedalitbang, (2022). Surabaya City Sanitation Strategy 2022-2026. Surabaya. **(226 pages)**.

Barragan-Fonseca, K.B.; Dicke, M.; van Loon, J.J.A., (2017). Nutritional value of the black soldier fly (Hermetia illucens L.) and its suitability as animal feed - a review. J. Insects Food Feed. 3(2): 105–120 **(16 pages)**.

Basri, N.E.A.; Azman, N.A.; Ahmad, I.K.; Suja, F.; Jalil, N.A.A.; Amrul, N.F., (2022). Potential applications of frass derived from black soldier fly larvae treatment of food waste: A review. Foods. 11: 2664 **(19 pages)**.

Brunner, P.H.; Rechberger, H., (2016). Practical handbook of material flow analysis. Lewis Publisher.

Budihardjo, M.A.; Sumiyati, S.; Sawitri, D.R.; Octaviani, Y.N.; Wati, H.R., (2023). Using material flow analysis (MFA) for waste management planning in Batang Regency. IOP Conf. Ser. Earth Environ. Sci., 1239: 0012029 **(8 pages)**.

Chalak, A.; Abou-Daher, C.; Chaaban, J.; Abiad, M.G., (2016). The global economic and regulatory determinants of household food waste generation: A cross-country analysis. Waste Manage. 48: 418–422 (**5 pages**).

Elissen, H.; van der Weide, R.; Gollenbeek, L., (2023). Effects of black soldier fly frass on plant and soil characteristics – a literature overview. Wageningen, The Netherlands. **(23 pages)**.

EU, (2021). Commission Regulation. 2021/1925.

Fadhillah, N.; Bagastyo, A.Y., (2020). Utilization of Hermetia illucens larvae as a bioconversion agent to reduce organic waste. IOP Conference Series: Earth Environ. Sci., 506: 012005 **(11 pages)**.

FAO, (2022). Tackling food loss and waste: A triple win opportunity.

FAO, (2024). Food Loss and Food Waste. In: Policy Support Gov. Gatew.

Farahdiba, A.U.; Warmadewanthi, I.D.A.A.; Fransiscus, Y.; Rosyidah, E.; Hermana, J.; Yuniarto, A., (2023). The present and proposed sustainable food waste treatment technology in Indonesia: A review. Environ. Technol. Innov. 32: 103256 **(16 pages)**.

Gao, Z.; Wang, W.; Lu, X.; Zhu, F., Liu, W.; Wang, X.; Lei, C., (2019). Bioconversion performance and life table of black soldier fly (Hermetia illucens) on fermented maize straw. J. Clean Prod., 230: 974–980 **(7 pages)**.

Gold, M.; Cassar, C.M.; Zurbrügg, C.; Kreuzer, M.; Boulos, S.; Diener, S.; Mathys, A., (2020). Biowaste treatment with black soldier fly larvae: Increasing performance through the formulation of biowastes based on protein and carbohydrates. Waste Manage. 102:319–329 **(11 pages)**.

Hegnsholt, E.; Unnikrishnan, S.; Pollman-Larsen, M.; Askeldottir, B.; Gerrad, M., (2018). Tackling the

1.6-Billion-Ton food loss and waste crisis. The Boston Consulting Group, Food Nation, State of Green.

Kavitha, S.; Kannah, R.Y.; Kumar G.; Gunasekaran, M.; Banu, J.R., (2020). Introduction: sources and characterization of food waste and food industry wastes. In: Banu, J.R (ed.) Food Waste to Valuable Resources. Elsevier Inc., 1–13 **(13 pages)**.

Kim, C.H.; Ryu, J.; Lee, J.; Ko, K.; Lee, J., Park, K.Y.; Chung, H., (2021). Use of black soldier fly larvae for food waste treatment and energy production in Asian countries: A review. Processes 9(1): 161 **(17 pages)**.

Lai, J.C.; Then, Y.L.; Hwang, S.S.; Lee, C.S., (2024). Optimal aeration management strategy for a small-scale food waste composting. Carbon Resour. Convers., 7: 100910 **(10 pages)**.

Lalander, C.; Diener, S.; Zurbrugg, C.; Vinneras, B., (2019). Effects of feedstock on larval development and process efficiency in waste treatment with balck soldier fly (Hermetia illucens). J. Clean Prod., 208: 211–219 **(9 pages)**.

MEFRI, (2024). National Waste Management Information System. Ministry of Environment and Forestry of the Republic of Indonesia.

MNDPRI, (2021). Study Report: Food Loss and Waste in Indonesia, Supporting the Implementation of Circular Economy and Low Carbon Development. **(116 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 city in Batu, Indonesia. IOP Conf. Ser. Earth Environ. Sci., 1165: 012005 **(7 pages)**.

Oshins, C.; Michel, F.; Louis, P.; Richard, T.L.; Rynk, R., (2022). The composting process. In: Rynk R (ed) The Composting Handbook: a how-to and why manual for farm, municipal, institutional and commercial composters. Elsevier Inc., 51–101 **(51 pages)**.

Raksasat, R.; Abdelfattah, E.A.; Liew, C.S.; Rawindran, H.; Kiatkittipong, K.; Mohamad, M.; Mohd Zaid, H.F.; Jumbri, K.; Lam, M.K.; Lim, J.W., (2022). Enriched sewage sludge from anaerobic pre-treatment in spurring valorization potential of black soldier fly larvae. Environ. Res., 212: 113447 **(8 pages)**.

Ratnawati, B.; Yani, M.; Suprihatin, S.; Hardjomidjojo, H., (2023). Waste processing techniques at the landfill site using the material flow analysis method. Global J. Environ. Sci. Manage., 9: 73–86 **(14 pages)**.

Rimantho, D.; Hidayah, N.Y.; Saputra, A.; Chandra, A.; Rizkiya, A.N.; Nashifah, G.; Fitriyani, P.; Wesha, D.M.P., (2022). Material flow analysis for assessing the sustainability solid waste management strategy. Int. J. Sustain. Dev. Plan., 7: 2271–2278 **(8 pages)**.

SCG, (2023). Volume Sampah Harian di Surabaya 60 Persen didominasi Organic.

SES, (2020). Information Document of Environmental Management Performance 2020 **(2318 pages)**.

Setti, L.; Francia, E.; Pulvirenti, A.; Gigliano, S.; Zaccardelli, M.; Pane, C.; Caradonia, F.; Bortolini, S.; Maistrello, L.; Ronga, D., (2019). Use of black soldier fly (Hermetia illucens (L.), Diptera: Stratiomyidae) larvae processing residue in peat-based growing media. Waste Manage., 95: 278–288 **(11 pages)**.

Skaf, L.; Franzese, P.P.; Capone, R.; Buonocore, E., (2021). Unfolding hidden environmental impacts of food waste: An assessment for fifteen countries of the world. J. Clean Prod., 310: 127523 **(9 pages)**.

Song, S.; Ee, A.W.L.; Tan, J.K.N.; Cheong, J.C.; Chiam, Z.; Arora, S.; Lam, W.N.; Tan, H.T.W., (2021). Upcycling food waste using black soldier fly larvae: Effects of further composting on frass quality, fertilizing effect and its global warming potential. J. Clean Prod., 288: 125664 **(14 pages)**.

Sundin, N.; Osowski, C.P.; Strid, I.; Eriksson M., (2022). Surplus food donation: Effectiveness, carbon footprint, and rebound effect. Resour. Conserv. Recycl., 181: 106271 **(14 pages)**.

Tetra Tech, (2021). Clean cities, blue ocean initial solid waste management assessment (ISWMA) | Indonesia. United States Agency for International Development. **(77 pages)**.

Thushari, I.; Vicheanteab, J.; Janjaroen, D., (2020). Material flow analysis and life cycle assessment of solid waste management in urban green areas, Thailand. Sustain. Environ. Res., 30: 21 **(17 pages).**

UNEP, (2021). Food Waste Index Report 2021. Nairobi. United Nations Environment Programme. **(132 pages)**.

WHO, (2023). The State of Food Security and Nutrition in the World. **(316 pages)**.

Widyarsana, I.M.W.; Damanhuri, E.; Agustina, E., (2020) Municipal solid waste material flow in Bali Province, Indonesia. J. Mater. Cycles. Waste Manag., 22: 405–415 **(11 pages)**.

Zahra, S.C., (2023). Material Flow Analysis of Food Waste in Jambangan Recycling Center and Wonorejo Compost House, Surabaya. Thesis. Surabaya. Institut Teknologi Sepuluh Nopember. **(79 pages)**.

Zakarya, I.A.; Yabainus, A.F.; Halis, R.; Beson, M.R., (2021). A comparative study on generation and composition of food waste in Kundasang, Sabah. IOP Conference Series: Earth Environ. Sci., 920: 012026 **(11 pages)**.

AUTHOR (S) BIOSKETCHES

Zahra, S.C., B.Eng. Student, Department of Environmental Engineering, Faculty of Civil Engineering, Planning, and Geo-Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.
- Email: *sazhachanifa5@gmail.com*
- ORCID: 0009-0001-4069-9683
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: http://enviro.its.ac.id/

Anggrainy, A.D., M.Eng., Part-time Researcher, Research Center for Infrastructure and Sustainable Environment, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
- Email: *anitadwia@gmail.com*
- ORCID: 0000-0002-9271-8604
- Web of Science ResearcherID: AAW-4732-2021
- Scopus Author ID: 57195303426
- Homepage: https://scholar.its.ac.id/en/

Mohd-Zaki, Z., Ph.D., Senior Lecturer, Civil Engineering Studies, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Permatang Pauh Campus, Pulau Pinang, Malaysia
- Email: *cezuhaida@uitm.edu.my*
- ORCID: 0000-0002-0201-5084
- Web of Science ResearcherID: NA
- Scopus Author ID: 36606522200
- Homepage: https://ppkapp.uitm.edu.my/

Bagastyo, A.Y., Ph. D., Professor, Department of Environmental Engineering, Faculty of Civil Engineering, Planning, and Geo-Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.
- Email: *bagastyo@enviro.its.ac.id*
- ORCID: 0000-0001-8850-9255
- Web of Science ResearcherID: R-6313-2019
- Scopus Author ID: 36668120400
- Homepage: http://enviro.its.ac.id/

HOW TO CITE THIS ARTICLE

Zahra, S.C.; Anggrainy, A.D.; Mohd-Zaki, Z.; Bagastyo, A.Y., (2024). Food waste reduction strategies in composting and recycling centers based on material flow analysis. Global J. Environ. Sci. Manage., 10(SI): 167-180.

DOI: 10.22034/gjesm.2024.10.SI.11

URL: https://www.gjesm.net/article_715533.html

Global J. Environ. Sci. Manage. 10(SI): 181-200, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Conversion of motorcycles to electric vehicles towards sustainable mobility

A.D. Santoso[1,*], H. Daulay[2], A. Priyanti[2], V.M.M. Silalahi[2], U.K. Yaumidin[2], N. Irawati[3], H. Sumartono[3], P. Astuti[4], A.R. Farandy[2], A. Parikesit[5], M.F. Manti[6], E. Indriasari[7], W. Joelijani[8], S. Wahyuni[2]

[1] *Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Jakarta, Indonesia*

[2] *Research Center for Behavioral and Circular Economy, National Research and Innovation Agency, Jakarta, Indonesia*

[3] *Research Center for Transportation Technology, National Research and Inovation Agency, Jakarta, Indonesia*

[4] *Research Center for Agroindustry, National Research and Innovation Agency, Jakarta, Indonesia*

[5] *Research Center for Appropriate Technology, National Research and Innovation Agency, Jakarta, Indonesia*

[6] *Maritime and Transportation Industry, Coordinating Ministry for Maritime Affairs and Investment, Jakarta, Indonesia*

[7] *Indonesian Land Transportation Polytechnic - Indonesian Land Transportation College, Ministry of Transportation, West Java, Indonesia*

[8] *Regional Research and Innovation, National Research and Innovation Agency, Indonesia, Jakarta, Indonesia*

ARTICLE INFO

Article History:
Received 16 March 2024
Revised 19 May 2024
Accepted 22 July 2024

Keywords:
Electric vehicle conversion
Converted battery-powered electric vehicle (CBEV)
Internal combustion engine (ICE)
Multidimensional scaling (MDS)
Sustainability.

ABSTRACT

BACKGROUND AND OBJECTIVES: Developing Southeast Asian countries, including Indonesia, have significant hurdles in addressing the increasing usage of motorized vehicles and their detrimental impact on air quality, traffic, energy security, liability, and greenhouse gas emissions. is to assess the viability of transforming traditional internal combustion engine motorcycles into electric vehicles powered by batteries in Indonesia. The analysis will concentrate on the positive environmental outcomes, including decreased greenhouse gas emissions and energy usage, in addition to examining the economic and social consequences of this transition. The absence of exhaust emissions could create the impression that converting to battery-powered electric vehicles will consistently yield favorable environmental outcomes, such as reducing greenhouse gas emissions and energy consumption. Meanwhile, the economic and social impacts associated with electric vehicle conversion programs are also taken into account savings during post-conversion.
METHODS: Primary data was acquired through the distribution of questionnaires, conducting in-depth interviews with workshop managers, and obtaining scientific evaluations from participating experts. The Rapfish multidimensional scaling application was used to handle and evaluate the data. The analysis of the data involved the examination of five dimensions, namely social, economic, ecological, technological, and institutional, with each dimension comprising 37 variables.
FINDINGS: The sustainability index, which stands at 70.39 percent, indicating a fair level of sustainability, implies that there is significant development potential in the conversion process of internal combustion engine motorbikes to battery electric vehicles by strategically focusing on key leverage factors across various dimensions. The institutional dimension registers the lowest value at 48.92 percent, whereas the environmental, technological, social, and economic dimensions' exhibit values of 85.25 percent, 79.13 percent, 76.29 percent, and 62.37 percent, respectively. Achieving sustainability requires focused enhancements in various key areas: setting up waste conversion facilities in the environmental aspect, educating employees on environmental conservation and boosting business incentives in the social aspect, ensuring a stable supply of raw materials and maximizing market penetration in the economic aspect, and improving experience management and skill acquisition in the technological aspect. Additionally, the presence of funding, the involvement of marketing intermediaries, and the backing for initiatives aimed at converting vehicles to electric power within the institutional framework are key aspects that demand concentrated efforts.
CONCLUSION: The multidimensional assessment indicates that Indonesia's electric vehicle conversion program is progressing effectively, achieving an average sustainability index of 70.39 percent, categorized as fair. The results indicate that the initiative has effectively created a resilient, sustainable conversion framework that can be tailored to various environments and scenarios. To further enhance sustainability within these conversion initiatives, it is imperative to prioritize institutional dimensions, particularly financial and marketing support, as well as the critical role of the electric vehicle conversion itself. This model provides significant perspectives for policymakers and government entities when developing and executing forthcoming policies and initiatives.

DOI: 10.22034/gjesm.2024.10.SI.12

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

NUMBER OF REFERENCES
68

NUMBER OF FIGURES
6

NUMBER OF TABLES
3

*Corresponding Author:
Email: *arif.dwi.santoso@brin.go.id*
Phone: +62 852 861 12334
ORCID: 0000-0003-5595-9265

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

The primary contributor to carbon dioxide (CO_2) emissions is the transportation industry's reliance on fossil fuels, leading to significant implications for both global climate change and abnormal weather patterns at the local level (Rubino *et al*. 2017). The growing number of automobiles on the road is driving up the demand for fossil fuels, which is predicted to continue to rise next year. Conversely, energy consumption is positively correlated with economic growth (Oryani *et al*., 2022). The anticipated figure for the total number of motorbikes in Indonesia by the end of 2022 is estimated to reach 125.3 million, showcasing a steady rise each year from 2012, with an additional 48.9 million units, equating to a growth of 64 percent (Ferlinda *et.al*., 2024). The transportation sector contributes around 27 percent (%) of greenhouse gases (GHGs) emissions, of which around 90% is generated by the land transportation subsector (WRI, 2023). The present circumstances demand the promotion of innovation and the implementation of strategies to decrease carbon emissions in the land transportation sector, in order to hasten the attainment of targets for reducing greenhouse gas emissions. This innovation is consistent with and supports the Minister of Transportation's achievements in establishing climate change mitigation actions in the transportation sector to meet Indonesia's National Defined Contribution (NDC) target (Wahyono *et al*., 2024). As part of the endeavor to diminish greenhouse gas emissions originating from the transportation sector, the government has set its sights on a program for converting 50,000 conventional motorbikes into electric motorbikes by 2023. Subsequently, the target has been raised to 150,000 units for the year 2024. To increase the acceleration of the conversion program, conversion subsidy funds of United States Dollar (USD) 340-620 have been distributed for each electric vehicle (EV) unit (Darmoyono, 2024). The significance of electric vehicles (EVs) lies in their role as pivotal technology for the future of automotive power systems, characterized by their silent operation, economical running costs, and lightweight construction (Zainol *et al*., 2019). The lack of electric car infrastructure is a key issue in the Southeast Asian automobile market, particularly in Indonesia. With its status as the world's largest country, Indonesia showcases immense potential. The automotive industry has started to allocate resources towards research and development efforts for EV. The number of EV has risen considerably in recent years, owing to technology advancements and government attempts to lessen their environmental impact. Government rules on EV remain a key non-technical hurdle, although charging times and battery performance are technical difficulties. It is imperative to assess and scrutinize the initiatives aimed at converting EV to ascertain the trajectory of the program's overall effectiveness and its ability to sustain long-term growth or decline. One of the reliable tools for monitoring and reviewing sustainability is multidimensional scaling (MDS) method. The MDS method provides a valuable means of assessing the sustainability index of a process or product production, allowing for the determination of its level of sustainable status. The project system that occurred failed to keep the environment sustainable, so this urged policymakers to the solution development of sustainability (Alder *et al*., 2000; Lloyd *et al*., 2022). As the sustainability concept is growing more important, instruments are needed to evaluate it. he significance of the sustainability index is growing as it is utilized to evaluate the progress of sustainable development, encompassing not just the economic sector but also the environmental and social impacts concurrently. It contributes to making a management policy more efficient and effective. This research will promote realistic MDS approaches to assist workshop machinery entrepreneurs in making product management strategy decisions. MDS can assist entrepreneurs in obtaining quantitative assessments of item similarity across groups. MDS has the capability to transform customer evaluations of similarity or preference (such as a fondness for a narrative or product) into distances within a multidimensional space. MDS has two main advantages: it allows for individual analysis by creating a perception map of as many things or topics as possible, which a multivariate approach does not allow for, and without the requirement to strictly measure product attributes, researchers can add dimensions. (Hout *et al*., 2013). Originally, Multidimensional Scaling (MDS) was employed for the purpose of suggesting fisheries policies. Nevertheless, it has also expanded into various fields, including ecology (Kenkel and Orloci, 1986), political science, sociology (Amato, 1990), and the

management of natural resources (Sulaiman *et al*., 2021). Research on determining sustainability index using MDS related to others topic has been widely reported by several authors, such as algae biomass production (Santoso *et al*., 2023), duck farming (Rohaeni *et al*., 2021; Bakrie *et al*., 2023), garlic (Paczka *et al*., 2021), chocolate (Fairuzia *et al*., 2020), compost (Santoso *et al*., 2023a), beef (Rohaeni *et al*., 2024), dairy (Lovarelli *et al*., 2020), buffalo (Rohaeni *et al*., 2023), shrimp (Sivaraman *et al*., 2019), rice (Rachman *et al*., 2022), coffee (Yusuf *et al*., 2022), black soldier fly (Santoso *et al*., 2023b), integrated farming (Widjaja *et al*., 2023), and sago (Allaily *et al*., 2024). Although research on sustainability has been conducted independently across various agricultural products. However, there remains a gap in the exploration of applying sustainability principles to evaluate machinery, particularly in the context of enhancing electric machine conversion efficiency. Efforts to make conversion program become a superior program for the future require some efforts to find out factors influence the sustainability of electric machinery industry. The study regarding the comprehension of the wider consequences and obstacles encountered in the conversion of electric vehicles has been documented. For instance, certain studies underscore the importance of solid infrastructure and policy reinforcement in guaranteeing the enduring feasibility of electric bicycles (Kumar and Alok, 2020). The adoption of electric bicycles is significantly influenced by consumer acceptance and behavior change, with incentives and awareness campaigns serving as crucial factors, as highlighted by Garg *et al*. (2023). This underscores the importance of conducting a thorough. Also important is the development of technologies such as battery management systems (Gabbar *et al*., 2019), battery charging (Collin *et al*., 2019), and battery recycling (Amusa *et al*., 2019). The evaluation of the sustainability of electric conversion holds significant importance in analyzing trade-offs in sustainability, establishing the extent of regulatory constraints within the automotive sector, engaging a wider range of stakeholders, and enabling enhancements in areas like planning and strategic initiatives to meet the future objectives of the automotive industry. Therefore, this study hypothesizes that the electric vehicle conversion program will support climate change mitigation program in addition to reducing GHGs emission also improves the environment quality. The practical approach of MDS provides information that can assist management decision-makers in electric vehicle conversion program. In this study, the MDS analysis is expected to assist the workshop entrepreneurs in making decisions about several alternative product machinery managements. The main goal of this study is to evaluate the sustainability index pertaining to the transformation of motorbikes from internal combustion engines to electric vehicle motorbikes within the context of Indonesia. Specifically, this research aims to assess the sustainability index for each dimension (social, economic, ecological, technological and institutional), and does not assess engine performance characteristics. Specifically, this research purposes to 1) Assess the sustainability index of each dimension (social, economic, ecological, technological, and Institutional); 2) Identify the factors that have a sensitive effect on the engine conversion system; and 3) Determine the most dominant factor in the engine conversion system. The present research project was carried out at the Research Centre for Behavioural and Circular Economy, National Research and Innovation Agency, Indonesia in 2024.

MATERIALS AND METHODS

Research materials and procedure

This study was carried out by examining data that centered on the transformation of a traditional internal combustion engine (ICE) motorcycle into a converted battery-powered electric vehicle (CBEV). The method of obtaining secondary data involves collecting data from research journals, and other literature related to the sustainability of machinery conversion program. Moreover, data was collected by conducting a Focus Group Discussion (FGD) and administering questionnaires to thirteen experts who have significant involvement, skill, and understanding of the electric conversion program. The qualifications of the experts involved in filling out the questionnaire are those who have at least 3 years' experience in electric conversion experiences. Based on the specified respondent criteria, several respondents were determined, including individuals from, the industrial department agency, members of automotive groups, and various experts associated with machine conversion program. Extensive literature

Table 1: 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

review and expert consultations were utilized to select the attributes, ensuring their relevance to the sustainability of the electric conversion program. Each attribute was then assigned a weight reflecting its importance, determined through a FGD method. The normalization of weights was carried out to guarantee that the total sum of weights equated to one, thereby improving the transparency and precision of the MDS analysis. In-depth interviews were carried out with management and conversion workshop operators to gather primary data, alongside scientific assessments provided by experts who participated as respondents. The data is then processed and analyzed with the MDS method. The Rapfish program was used to do MDS analysis program (Pitcher and Preikshot, 2001).

Data analysis

The sustainability of the electrical conversion program was assessed utilizing a multidimensional scaling (MDS) approach and the Rapid Appraisal (Rap) conversion machine conversion analysis tool. The identified attributes demonstrate the degree of sustainability across various dimensions, with adjustments made based on the information accessibility pertaining to the specific resource (Kavanagh and Pitcher, 2004). There are five dimensions: environmental, economic, social, technological, and institutional, with 37 attributes in all (Table 2). A questionnaire with likert-scale response options is used to describe the dimensions and attributes. The questionnaire response sheet allows expert participants to rate items as either low, moderate, or high by assigning numerical values of 0, 1, or 2 respectively. In the realm of MDS, two distinct points or objects are graphically represented by points that are closely situated. Widely separated points were employed to denote items or points that differed from each other (Alder *et al*., 2000). In MDS, ordination or distance determination approaches were based on the Euclidian distance in n-space using Eq. 1 (Lloyd *et al*., 2022):

$$d = \sqrt{\left(\left|x_1 - x_2\right|^2 + \left|y_1 - y_2\right|^2 + \left|z_1 - x_2\right|^2 + \ldots\right)} \quad (1)$$

In MDS, configurations of objects or points were estimated by regressing Euclidian distance (dij) from point i to point j with point of origin (oij) using Eq. 2 (Lloyd *et al*., 2022):

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (2)$$

The ALSCAL algorithm was employed for the regression analysis of Eq. 2. The ALSCAL method optimizes squared distance (squared distance = d_{ijk}) against squared data (point of origin = o_{ijk}), which in three dimensions (i, j, k) is called S-Stress using Eq. 3 (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):

$$d_{ijk} = \sum_{a=1}^{r} w_{ka}\left(x_{ia} - x_{ja}\right)^2 \quad (4)$$

EV conversion sustainability analysis

The levels of sustainability performance of EV conversion are divided into 4 levels, resulting in intervals of 0, 25%, 50%, 75%, and 100%. The assessment categories are as follows: 0.00 - 25, poor category and unsustainable; 25.01 - 50, less category, less sustainable; 50.01 - 75, adequate category, fairly sustainable; 75.01 - 100.00, good category sustainable (Arofi *et al*., 2015). Employing analysis techniques can also assist in pinpointing characteristics that are attuned to sustainability considerations. The indicator with the highest root mean square (RMS) value is the most sensitive (Pitcher and Preikshot, 2001). 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) according to Pitcher and Preikshot, (2001). Table 1 presents the factors that have an impact and are dominant.

Table 2: List of dimensions and their attributes

Environment	Economy	Social	Technology	Institution
1. Electrical energy efficiency	8. Productivity	15. Education level of manager	23. Adoption of conversion system	29. Existence of corporation
2. Noisy pollution	9. Management level	16. Business motivation	24. Specialization or skills required	30. Existence role of conversion program
3. Water efficiency	10. Business success rate	17. Public unrest potential	25. Facilities and infrastructure	31. stakeholders supporting
4. Water pollution	11. Welfare of managers/workers	18. Job losses potential	26. Increasing technology conversion	32. Procedures for receiving government assistance
5. Air pollution	12. Availability of raw materials	19. Workers' knowledge of environmental preservation	27. Level of method sensitivity	33. Existence of entrepreneurs' community
6. Machines and parts waste	13. Market absorption of conversion services	20. Work accidents potential	28. Worker capacity building program	34. Existence of finance agency
7. Treatment facilities for waste parts	14. Salary	21. Potential job creation for local residents		35. Marketing agency supporting
		22. Salary gaps between workers		36. Supporting from research agency
				37. Existence of waste management unit

Monte Carlo analysis helps in determining the error, assessing the uncertainty in MDS. If the discrepancy between the MDS value and Monte Carlo value is small, it indicates that the MDS analysis for determining sustainability is sufficiently accurate with a 95% confidence level.

RESULTS AND DISCUSSION

The MDS technique was implemented to generate the sustainability index value for the ICE to CBEV conversion process and to identify variable features. The MDS dimensions measured include the five dimensions and all of their attributes. Utilizing a scientific assessment questionnaire, the input data for this calculation was obtained. Furthermore, this analysis will uncover sensitive attributes and influential variables that play a role in the sustainability of the process.

Index of sustainability

Scientific evaluation of the attributes within each dimension of sustainability is crucial for accurately estimating the sustainability index level. The consideration of specific and temporal characteristics is crucial in the determination of an attribute. (Pitcher and Preikshot, 2001). The attribute of all dimensions consists of environmental, economy, social, technology, and institutional that presented in Table 2.

Attribute of environmental dimension was consisting of noisy, water, and air pollution; water efficiency; waste of machinery part treatment. Meanwhile, social dimension attributes are determined by education level, corporate motivation, the possibility of public unrest, understanding of environmental conservation, and job loss. The economic dimension of a business includes factors such as the salary and welfare of workers, productivity levels, and the ability of the service market to absorb goods and services. Technology attributes include conversion system adoption, technological improvement possibilities, worker capacity building programmes, facilities and infrastructure, and management experience and skills. The ultimate institutional feature includes the presence of a corporation or agency that offers support for the program, along with the function of conversion program. To establish the level of sustainability in each process of converting an ICE motorcycle into a CBEV, the attributes in every dimension were created in a sheet questionnaire and submitted to the relevant scientific judgment. Additionally, the MDS approach and the Rapfish program were utilized to assess the

Table 3: The results of sustainability index for the five dimensions and its associated data quality statues

Dimension	Index (%)	Status	Stress	R^2 (Structured query reporter: SQR)
Environmental	85.24	good	0.1397	0.9429
Social	76.29	good	0.1385	0.9484
Economical	62.37	fairly	0.1442	0.9416
Technological	79.13	good	0.1469	0.9439
Institutional	48.92	unsustainable	0.1351	0.9498
Average	70.39	fairly		

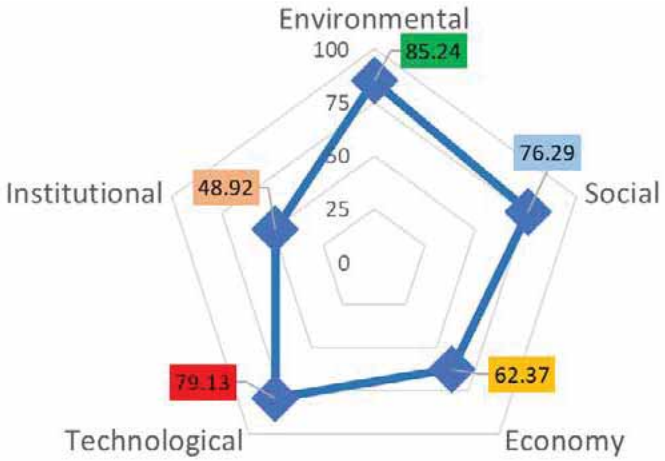


Fig. 1: Sustainability status of CBEV conversion program

expert's evaluation results. The sustainability index calculation results were outlined in Table 3.

MDS analysis findings for the performance of CBEV program are 70.37% on a sustainability scale of 0-100, with R^2 (SQR) > 0.94, indicating that it is quite category and fairly sustainable. This value represents the culmination of appraising 37 attributes across five distinct dimensions. The environmental dimension has an index value of 85.24%, the social dimension has 76.29%, the economic dimension has 62.37%, the technological dimension has 79.13%, and the institutional dimension has 48.92%. The results of the sustainability analysis can be seen in Fig. 1 and Table 3.

Environmental dimension

Among the various aspects, the environmental dimension stands out by providing the greatest value, as evidenced by a sustainability index score of 85.24%. The attribute that has the highest impact, at 4.65%, is the accessibility of treatment facilities for waste materials that can be utilized by others. On the other hand, the most impactful environmental attribute was generated of air and water pollution (3.16-3.44%) (Fig. 2). The increase in the number of workshops, both small and large scale workshops, as a result of this conversion program will increase the potential for workshop waste which can cause serious problems for the environment. The process of electric vehicle conversion entails the transformation of traditional fossil fuel-based vehicles into electric vehicles through the replacement of internal combustion engines and fuel delivery systems with electric motors and rechargeable batteries (Zaenuri *et al.*, 2023). The waste produced by the workshop is divided into two, namely: metal solid waste (pieces of metal nuts/screws, used welding waste) and non-metal (used tires/rubber, foam, synthetic leather, used rags or fabrics that have been contaminated by oil/ solvent, dry paint, etc.) (Tchobanoglous *et al.*, 2014). Waste generated during the conversion process includes engine and fuel system components extracted from the motor body, as well as supplementary part kits that enhance fuel engine functionality (Matasova and Tupov, 2020). In order to mitigate the impact of this waste, workshop

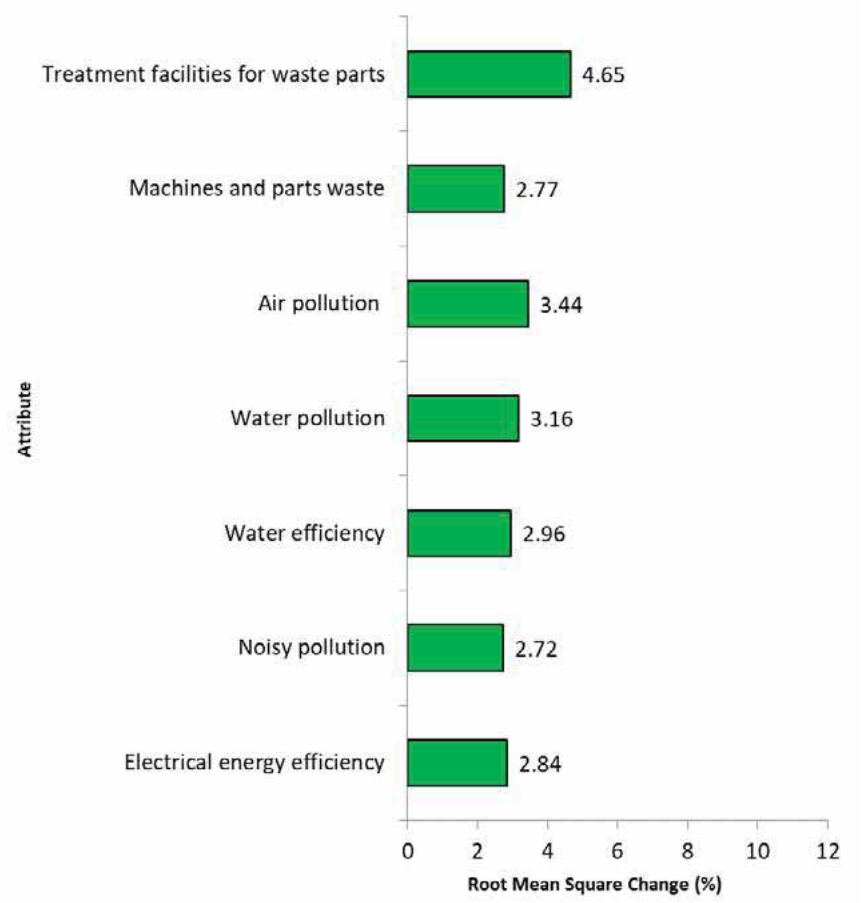


Fig. 2: Leverage of environment attributes

owners should prioritize a number of waste handling initiatives. Waste fuel engine systems can be utilized and modified to become motors that drive several agricultural machines or small industrial machines, such as grass cutters, corn harvesting machines, food chopping machines, etc. (Bouchiat *et al*., 2023). Utilization and modification of motors into various new machines necessitates the modification of their transmission systems. This is due to the fact that motorcycle engines, known for their high torque, need to be adjusted to suit the specific torque power requirements of the new machines, which may call for medium or low torque power (Lomonova *et al*., 2002).

It is important to anticipate the disposal of other motorbike parts, such as exhaust systems, cables, and fuel systems, in order to minimize their environmental impact. Therefore, it is recommended that every conversion workshop have a waste treatment facility unit (Salem *et al*., 2023). For small workshops that still do not have waste facilities, the workshop is expected to have a standard operation procedure (SOP) for waste management that regulates the management of conversion part waste for processing to other parties (Andriyani *et al*., 2024). It is crucial to consider the possibility of water and air pollution during the conversion process. Electric vehicles have the potential to decrease greenhouse gas emissions by 4.5% in countries like Indonesia through the implementation of recycling within a closed-loop cycle (Sakunai *et al*., 2021). The hybrid electric vehicles (HEV) confirmed an excellent alternative to battery electric vehicles (ICEV), showing good compromise between global warming (GW) impact (85% with respect to the ICEV), terrestrial acidification, and particulate formation, similar to the ICEV (Pipitone *et al*., 2021). Water

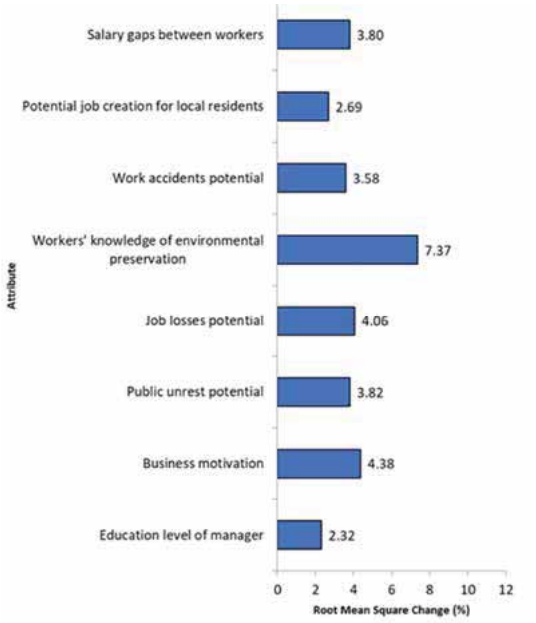


Fig. 3: Leverage of social attributes

pollution may come from waste motor oil and other motorbike waste that flows into the water drain. In order to prevent water wastage, it is essential to establish workshops with a more precise layout and conversion area to avoid the contamination of public drains with oil and other waste materials. The collected waste oil can be distributed to other parties to be reused (Tchobanoglous *et al*., 2014).

Social dimension

Based on the MDS Sustainability Index analysis of the converted electrical motorcycle program, the sustainability index value of the dimension was 76.29%, indicating a fairly sustainable state. This implied that the societal involvement in the sustainability of the converted electric motorcycle project was quite favorable. The leverage analysis results for the social dimension showed that workers' knowledge of environmental preservation, business motivation, and job loss potential were the attributes with a dominant influence on the sustainability index value. According to Habibie *et al*. (2022), the shift from conventional motorcycles to electric motorcycles could result in possible job displacement, suggesting that those who make the switch will enjoy additional. Using an ICE motorcycle requires queuing at gas stations for refueling. In addition, they need to allocate time to maintain the engine and other parts at a motorcycle workshop, while electric motorcycle owners do not need to maintain the electric motor engine at a workshop. Meanwhile, the job loss potential attribute, as discussed in Heylen *et al*. (2020), shows that training provides significant and measurable benefits for welfare and economic growth without causing significant negative impacts on the environment. This approach has the capability to target additional influential factors (characteristics) within the societal realm, including the risk of unemployment resulting from the shift from motorcycles to electric vehicles. The leverage analysis results for the social dimension (Fig. 3) showed that out of the eight attributes analyzed, three sensitive attributes significantly influenced the sustainability of the activity, workers' knowledge of environmental preservation, business motivation, and job loss potential.

The close connection between the social and economic dimensions is further highlighted by the correlation between business incentives, the market adoption of conversion services, and the rate of business success. Huang *et al.* (2021), revealed that technological knowledge is positively related to someone's intention to adopt EV. The manager's level of education and the potential for job creation among



Fig. 4: Leverage of economic attributes

local residents are two social dimension attributes that exhibit minimal impact on the sustainability of the activity. This indicates that electric motorcycle conversion activities do not require managers with a high education level, as some industries have developed plug-in conversion kits. Therefore, workshop managers with a Bachelor's degree or even a Vocational High School education level and at least 2 to 5 years of experience in motorcycle workshops are sufficient, as stated by Sari *et al*. (2020) that the most important factors are coaching and training. Job opportunities for local residents are primarily available during the early phase of motorcycle conversion to electric vehicles. However, these opportunities are expected to diminish considerably as the demand for converting fossil fuel motorcycles decreases over time.

Economic dimension

The MDS analysis has shown that the sustainability index for the economic dimension is 62.37%, a bit below the overall average of 70.39% (Table 4). This indicates that the economic dimension is in the adequate category (Arofi *et al*., 2015), contributing to the total average of 88.61% for all dimensions. With a stress value of 0.1385 and an R2 of 0.9484, the sustainability index demonstrates strong validity (Table 3). The attribute of market absorption of conversion services has shown the highest RMS change of 7.20% among the other six attributes in the leverage of economic dimension (Fig. 4). This indicates that market absorption of conversion services intends to be riskier due to the CBEV program being considered a new product and not widely known by the public. The disparity in supply and demand for BEV necessitates the enhancement of pricing and commercialization strategies to address market uncertainty. Proof and Focjik (2016) stated that information acceleration can improve traditional linear customer information acquisition approaches. This resulted in the calculation of appropriate pricing and marketing strategies during the initial stages of decision-making, thereby enhancing decision-making processes in the face of market unpredictability. In addition, the complexities surrounding BEV diffusion emphasize the importance of assessing

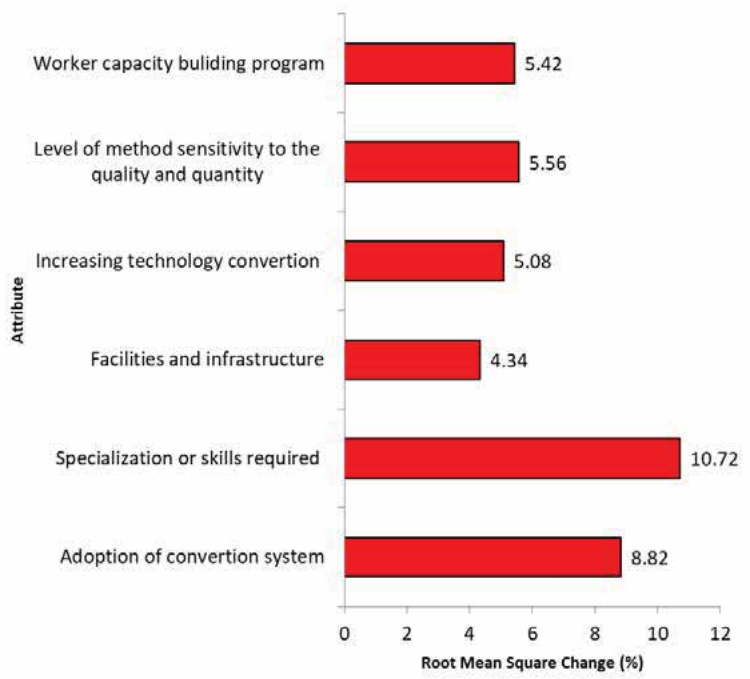


Fig. 5: Leverage of technology attributes

market penetration from an integrated perspective, considering the interaction between technology and behaviour (Martino *et al*., 2012). Neubauer and Pesaran (2013) have previously demonstrated that the elevated expenses associated with battery replacement and apprehensions regarding costs can dissuade prospective purchasers. This, in turn, could exacerbate the ambiguity surrounding the market acceptance of BEV conversion services. The importance of raw materials availability in production ranked second in the leverage of economic dimension with the RMS change of 6.03. This is very crucial due to the emerging nature of BEVs. Despite the accessibility of batteries and various components in the market, their prices remain relatively high, underscoring the obstacles confronting the industry. Karabelli *et al*. (2020) pointed out that the demand for critical materials for BEV's components underscores the necessity to ensure a stable supply chain to support the growth of sustainable mobility solutions. Furthermore, the strategic importance of sourcing raw materials goes beyond the production of battery BEV, presenting a wider obstacle for the technology industry in developed countries (Helmers, 2014). Efforts to address these challenges require collaboration among stakeholders along the entire supply chain, including processing industries, raw material suppliers, recycling companies, policymakers, and the public. Another element to consider is the characteristic of business success rate, which demonstrates an RMS fluctuation of 5.81%. This indicates that business success in BEV conversion services is a relatively new business in Indonesia requiring special attention. Several factors influence this, including public awareness campaigns (Sabyasachi *et al*., 2024). It is essential to implement these campaigns in order to efficiently expand BEV conversion services and accommodate the growing demand. Despite the readiness of workshops to serve customers based on field results, the current low demand is leading to a decreased rate of business success. Additionally, simplifying business processes involving government collaboration is essential, as the conversion process requires official vehicle documentation changes, which can be time-consuming. Therefore, as Ma and Yang (2024) explained, collaboration between the government and the private sector is vital for fostering innovations, ultimately enhancing the success rate of BEV conversions.

The study is primarily concerned with evaluating the sustainability of transitioning motorcycles to electric vehicles in Indonesia. The three attributes that are considered critical to achieve economic sustainability are market absorption of conversion services, availability of raw material, and may affect the success of the conversion motorcycles services business. Hence, the study has not yet examined the economic consequences concerning the expenses linked to costs and the possible reductions in fuel and maintenance expenditures. A previous study by Suwignyo *et al*. (2022) has found that converting to electric vehicles may save up to 68% of their income. In addition, the research conducted by Imansuri *et al.* (2023) revealed that the production cost per unit for electric conversion motorcycles in Indonesia is estimated to be USD 645.

Technological dimension

The findings from the sustainability analysis of the five attributes indicate that the technology aspect demonstrates sustainability, as evidenced by a sustainability index score of 79.13%. This has shown and supports the results of research conducted by Vacchi *et al*. (2021) that technology can be seen as a key dimension of sustainability along with the environment, society, and economy. In the technology dimension, the attributes that have the greatest influence is the specialization of skills required with a value of 10.72%, and adoption of conversion system with a value of 8.82%. Many scholars have explored the process of converting ICE vehicles into EVs through their research efforts (Ubaid *et al*., 2023; Gunawan *et al*., 2022). In line with this, the components needed to convert a conventional motorbike into an electric motorbike have been made in the form of a component package, making the conversion work easier. However, it is very necessary to have adequate worker skills in the mechanical and electrical fields. It is evident that specialized knowledge and skills, particularly in the areas of mechanics and electricity, are crucial for the successful transition of traditional motorcycles to electric motorcycles within the technological aspect of sustainability. Apart from that, it can be seen in the technology dimension table that adoption of the conversion system attribute has a high value, namely 8.82%. The attribute of method sensitivity to quality and quantity has showed an RMS score of 5.56%. It is imperative to establish regulations for this conversion program in order to address both technical and safety considerations, thereby safeguarding the well-being of users.

The relevant regulations are outlined in the Ministry of Transportation Regulation No. 39 of 2023. Every motorcycle that has undergone conversion and is intended for road use must meet technical and roadworthiness requirements to ensure safety. Type A workshops are responsible for conducting testing on converted motorcycles that possess a type test certificate derived from per-type testing, ensuring quality control measures are met. Several components are examined, including the battery pack, direct current (DC) to DC converter, electric motor, controller/inverter/electronic control unit, charger port, and other supporting equipment. The battery pack should undergo testing by a recognized institution to ensure compliance with either Indonesian national or international standards. Additionally, it should be securely mounted on the motorcycle using appropriate locking mechanisms. These type A workshops play a crucial role in maintaining standardization to support safety aspects of converted electric motorcycles. The demonstration illustrates the significant influence of this characteristic on the sustainability of technology. The simplicity of integrating the conversion system within local communities is expected to stimulate the proliferation of conversion workshops operating as micro, small and medium enterprises (MSMEs). This is in line with the research results presented by Osatis and Asavanirandorn (2022), that with the growth of conversion workshops, the need for skilled engineering-based personnel, especially Mechanical Engineering and Electrical Engineering, who come from automotive and electrical vocational schools, will increase.

Institutional dimension

The sustainability of the program to convert ICE motorcycles to CBEV motorcycles in Indonesia faces several challenges due to existing institutional arrangements. The obstacles encompass regulatory disintegration, collaboration among governmental bodies, enhancement of capabilities, and financial structures. It is imperative for the government of Indonesia to create a comprehensive electric vehicle ecosystem, with a strong emphasis on the



Fig. 6: Leverage of institutional attributes

implementation of integrated policies, infrastructure enhancement, and engagement with stakeholders (Hasudungan *et al*., 2023). Based on the MDS analysis using a Rapfish program, the sustainability index for the institutional dimension stands at 48.92%, with a stress value of 0.1351 and an R square of 0.9498, indicating a high degree of model fit and reliability in the data quality. Institutional sustainability index contributes to the lowest value between the other dimensions. The entrepreneurial community, financial agencies, and marketing agencies are identified as the three most significant attributes, with percentages of 7.52%, 7.04%, and 6.53% respectively. A waste management unit is critical in handling the disposal and recycling of old motorcycle parts and batteries, ensuring environmental sustainability. The significant contribution (4.70) emphasizes the importance of environmental management in facilitating the conversion program. This analysis suggest that every conversion workshop should have a waste treatment facility unit (Salem *et al*., 2023). Research agencies provide essential data, technological advancements, and innovation necessary for the successful implementation of the conversion program. The modest contribution (2.32) suggests potential for greater engagement and backing from research organizations. Marketing agencies play a crucial role in promoting the conversion program, raising public awareness, and driving consumer adoption. This significant

contribution (6.53) underscores the importance of effective marketing strategies in program success. The high contribution score (7.04) for financial institutions in supporting the conversion of ICE motorcycles to CBEV motorcycles in Indonesia highlights the critical role of financial support in facilitating this transition. The significance of loans, subsidies, and financial incentives is evident in addressing the economic obstacles linked to the initial substantial expenses of conversion and adoption. In Indonesia, integrating financial institutions into the conversion program could provide the much-needed push for widespread adoption. Robust financial support mechanisms will be essential in ensuring the program's success and long-term viability. However, funding mechanism is identified too complicated and takes too long. Governments around the world are taking a leading role in hastening this transition through the provision of incentives and subsidies aimed at boosting the uptake of electric vehicles. One significant effect of government incentives is the lowering of the upfront expenses associated with electric vehicles. This makes EVs more competitive with ICE vehicles, especially in terms of total cost of ownership. Consumers are more likely to consider an electric vehicle when they see it as an economically attractive option. It is crucial to have streamlined and easily accessible processes in place for individuals to obtain government aid in order to promote engagement in the conversion initiative at Rp 10 million per unit. This incentive value has increased from the previous Rp 7 million per unit. The increase in the electric motorcycle conversion incentive is stipulated in the Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 13 of 2023. The presence of entrepreneurial communities is pivotal in stimulating innovation and opening up avenues for business development, particularly in the sphere of transforming combustion engine motorcycles to electric motorcycles. This influence is reflected in the highest contribution score (7.52) in the sustainability index. The presence of a vibrant entrepreneurial community can drive the innovations and adoption of new technologies (Zhang *et al*., 2024), such as electric motorcycles, by providing a supportive ecosystem for start-ups and established businesses alike. It is crucial to have streamlined and easily accessible processes in place for individuals to obtain government aid in order to promote engagement in the conversion initiative. The minimal contribution (0.37) indicates a need for improving the efficiency and accessibility of government assistance programs. Support from various stakeholders, including industry players, government agencies, and non-profits, is crucial for a cohesive and coordinated effort. The minimal level of contribution (1.03) indicates the necessity to enhance stakeholder engagement and support. The conversion program itself must be well-defined, managed, and integrated into broader sustainability initiatives. The significant contribution (5.95) demonstrates the program's central role in achieving sustainability goals. Corporate engagement, by means of financial backing and active involvement, has the potential to propel significant advancements and creativity in the process of conversion on a massive scale. The moderate contribution (4.84) indicates that while corporations play a crucial role, there is potential for increased corporate engagement. Corporate engagement, by means of financial backing and active involvement, has the potential to propel significant advancements and creativity in the process of conversion on a massive scale.

With an overall sustainability index of 48.92%, the analysis highlights the substantial contributions of financial support, marketing, and entrepreneurial communities. Nevertheless, it also highlights areas that require enhancement, including government aid processes and involvement of stakeholders. The high R square value (0.9498) confirms the reliability of these findings, providing a robust framework for policymakers and stakeholders to enhance the sustainability of the conversion program.

Future and prospect for engine conversion program

The shift from traditional combustion engine vehicles to electric vehicles, such as electric motorcycles, has garnered significant attention from countries globally as they strive to transition their transportation energy towards meeting the net zero emission goals established by numerous nations. By using electric vehicles, dependence on fossil fuels will be reduced, as will fuel imports, contributing to energy stability and security in the future. Especially for oil-importing countries, fluctuations in oil prices significantly impact the economy. A potential method to incentivize the transition of vehicles to electric models involves a program focused on converting ICE motorcycles to CBEV motorcycles. From the results

of various sustainable dimensions, we can see that various efforts are needed to push this conversion program. Considering the number of motorcycles, 125.3 million units in 2022, this conversion program is indeed very attractive and necessary to reduce various issues such as fuel imports, fuel subsidies, and air pollution. The apprehensions regarding waste generated by the motorcycle conversion process have unveiled potential business prospects in the form of reusing or recycling components to create fresh raw materials. Additionally, by converting to CBEV motorcycles, users gain various benefits, including having more free time since they do not need to queue at gas stations for refueling, and not needing to maintain electric motors at workshops due to minimal maintenance requirements. From an economic standpoint, utilizing electric motorcycles is far more cost-effective than using ICE motorcycles, given that the operational and maintenance expenses of CBEV motorcycles are notably reduced in comparison to ICE motorcycles. Moreover, converting millions or tens of millions of motorcycles will build ecosystems such as the lithium battery industry, electric motors, and controllers that require tens of millions of components for conversion. Additionally, the implementation of the program will require many conversion workshops with skilled technicians to carry out the conversions. The skill in converting motorcycles can be elevated to further the development and construction of CBEV motorcycles. Currently, the government provides a subsidy of 10 million rupiahs per converted motorcycle unit to cover the high initial costs of conversion and adoption. In the event that this conversion program achieves economic feasibility, the costs associated with the conversion will decrease, thereby presenting an appealing prospect for financial institutions to offer loans for the execution of this conversion.

CONCLUSION

The sustainability of transitioning ICE motorcycles to CBEVs in Indonesia is noteworthy, especially when evaluated from five critical perspectives: environmental, social, economic, technological, and institutional. However, the institutional dimension lags in terms of environmental friendliness. The development of a conversion program necessitates careful consideration of 37 critical characteristics, with certain attributes requiring targeted enhancement due to their substantial influence on the overall sustainability of the program. The conversion of electric vehicles in Indonesia presents a notable sustainability potential in terms of the environmental aspect, as evidenced by a substantia sustainability index score of 85.24%. Effective waste management, particularly in workshops, is crucial to mitigate the environmental impact of increased workshop waste, which includes both metal and non-metal waste from the conversion process. The adaptation and utilization of waste fuel engine systems in agricultural and industrial equipment can help mitigate environmental impacts. Workshops should establish waste treatment facilities or standard operating procedures for waste management to prevent air and water pollution, thus ensuring that the environmental benefits of electric vehicle conversion are maximized. The electric motorcycle conversion program in Indonesia exhibits a relatively sustainable social dimension, boasting a sustainability index value of 76.29%. Key factors influencing this sustainability include workers' knowledge of environmental preservation, business motivation, and potential job loss. While electric motorcycles reduce time spent on refuelling and maintenance, job losses in traditional motorcycle services can be mitigated through training programs that support economic growth without harming the environment. The correlation between social and economic aspects highlights the significance of market penetration and the rates of business achievement. Workshop managers are not required to possess extensive educational credentials; practical experience and training are deemed satisfactory for the role. However, job creation from the conversion process is mainly limited to the initial stages, decreasing as the number of internal combustion engine motorcycles diminishes. The economic dimension of the electric motorcycle conversion program in Indonesia has a sustainability index of 62.37%, indicating it is adequate but below the overall average of 70.39%. The market absorption of conversion services is the most influential factor, with significant risks due to the novelty of BEV and market uncertainties. Improved pricing and commercialization strategies are essential to address this. The availability and cost of raw materials, especially batteries, present further challenges, requiring a stable supply chain and stakeholder collaboration. Business success rates are currently low due to limited demand, underscoring the need for public awareness campaigns and

streamlined government collaboration for vehicle documentation changes. Overall, the key to improving the sustainability and prosperity of BEV conversion services lies in addressing these economic challenges. conversion services. The technological dimension of the electric motorcycle conversion program in Indonesia is sustainable, with a high sustainability index value of 79.13%. The specialization of skills and the adoption of the conversion system are the most influential attributes, emphasizing the need for workers skilled in mechanical and electrical fields. The ease of implementing the conversion system fosters the growth of conversion workshops, increasing demand for skilled personnel from vocational schools. Continuous capacity building for employees is essential to keep pace with technological advancements and improve workshop innovations. Overall, developing competencies via formal and informal education is essential for maintaining the technological aspect of the transformation initiative. The institutional dimension of the electric motorcycle conversion program in Indonesia faces significant challenges, reflected in a sustainability index value of 48.92%. Key issues include regulatory fragmentation, coordination between government agencies, and complex funding mechanisms. Vital components for enhancement include the backing from entrepreneurial networks, financial establishments, and marketing firms, all of which have pivotal functions in encouraging acceptance and easing the shift. Overall, the electric motorcycle conversion program in Indonesia exhibits strong potential in environmental and technological sustainability, driven by effective waste management and the need for skilled labor. However, significant challenges remain in the economic and institutional dimensions. Addressing these challenges through better market strategies, financial support, and regulatory coordination is crucial for enhancing the program's overall sustainability and success. Quantitative metrics, such as sustainability index ratings and enhancements to specific attributes, offer a precise guide for focused enhancements and emphasize the significance of a comprehensive strategy in attaining sustainable conversion to electric vehicles.

AUTHOR CONTRIBUTIONS

A.D. Santoso conducted the literature review, designed the experiments, oversaw the work, and wrote the manuscript; H. Daulay conducted a literature study, experimented, and authored and edited the manuscript; A. Priyanti assisted with experimental and administrative tasks, as well as providing technical and material support; U.K. Yaumidin conducted a thorough analysis of the manuscript's substantial worth. N. Irawati assisted with experimentation and data collection; H. Sumartono analyzed and interpreted the data; The statistical analysis was performed by V.M.M. Silalahi; P. Astuti prepared and revised the manuscript; A.R. Farandy edited and supervised written works; A. Parikesit was in charge of overseeing all experimental and textual works; M.F. Manti is responsible for the manuscript's validation and generation; W. Joelijani was responsible for the manuscript's creation, validation, and generation; E. Indriasari connects literature evaluation and data recognition; S. Wahyuni assisted with experimentation and data collection.

ACKNOWLEDGMENTS

The authors are grateful to the National Research and Innovation Agency, and the Educational Endowment Fund Institute (LPDP) - Indonesia for funding this research through the Advanced Indonesia Research and Innovation Program (RIIM) [Batch IV Nomor 37/11.7/HK. 2023]. The authors would like to thank the editors and anonymous reviewers for their constructive feedback.

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

©2024 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
ASCAL	Multidimensional scaling, other name biside MDS
BEV	Battery-powered electric vehicle
BPS	Badan pusat statistik (Central Bureau of Statistics)
CO_2	Carbon dioxide
CBEV	Converted battery-powered electric vehicle
d	Euclidian distance
d_{ij}	Euclidian distance from point i to point j
d_{ijk}	Squared distance
Eq	Equation
EV	Electric vehicle
Fe	Iron
FGD	Focus group discussion
GHGs	Greenhouse gases
I, J, K	Dimension
ICE	Internal combustion engine
MDS	Multidimensional scaling
MSMEs	Micro, small and medium enterprises
NDC	National determined contribution
O_{ijk}	Point of origin
Rapfish	Rapid appraisal for fisheries
S	Stress
SOP	standart operation prosedure
SQR	Structured query reporter
USD	United state dolar
Rap	Rapid appraisal
RMS	Root mean square
R^2	Root mean square
y	Year

REFERENCES

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**).

Alder, J.; Pitcher, T.J.; Preikshot, D.; Kristin, K.; Ferriss, B., (2000). How good is good? A rapid appraisal technique for evaluation of the sustainability status of fisheries of the North Atlantic. Fisheries Centre, University of British Columbia, Canada **(47 pages)**.

Amato, P.R., (1990). Dimensions of the family environment as perceived by children: A multidimensional scaling analysis. J. Marriage Fam., 52(3):613–620 (**7 pages**).

Amusa, H.K.; Sadiq, M.; Alam, G.; Alam, R.; Siefan, A.; Ibrahim, H.; Raza, A.; Yildiz, B., (2024). Electric vehicle batteries waste management and recycling challenges: A comprehensive review of green technologies and future prospects. J. Mater. Cycles Waste Manage., 26:1959–1978 (**20 pages**).

Andriyani, N.; Suprobo, P.; Adi, T.J.W.; Aspar, W.A.N.; , Jatmiko, A.D.; Santoso, A.D., (2024). Integrating urban building information modeling and circular economy framework for green sustainablility. Global J. Environ. Sci. Manage., 10(3): 1313-1332 (**20 pages**).

Arofi, F.; Rukmana, D.; Ibrahim, B., (2015). The analysis of integration sustainability of coffee plantation and goat husbandry: A case study in Ampelgading subdistrict, Malang Regency, East Java, Indonesia. J. Economics Sustainable Dev., 6(10): 1-8 (**8 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. Plan., 18(10): 3181-3193 (**13 pages**).

Bouchiat, R.; Veignie, E.; Kaczmarek, F.; Dorchy, J.; Fortunato, A.D.; Rafin, C.A., (2023). A comprehensive review of risk assessments of organic effluents in car workshops. Environments. 10(12): 220 (**15 pages**).

Collin, R.; Miao, Y.; Yokochi, A.; Enjeti, P.; Von Jouanne, A., (2019). Advanced electric vehicle fast-charging technologies. Energies. 12(10): 1839 (**26 pages**).

Darmoyono, I., (2024). Study on challenges and opportunities for electric vehicle development for land-based public transport sector in cities of Indonesia. The Economic and Social Commission for Asia and the Pacific (ESCAP). Jakarta.

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).**

Ferlinda, I.; Pujiyanto, E.; Hisjam, M., (2024). Analysis of sustainable business models in electric motorcycle rental. E3S Web of Conference. 517: 05012 **(6 pages)**.

Gabbar, H.A.; Othman, A.M.; Abdussami, M.R., (2021). Review of

battery management systems (BMS) development and industrial standards. Technologies. 9(2): 28 (**23 pages**).

Garg, P.; Kumar, A.; Mittal, R.K., (2023). What drives consumers' sustainable mobility behavior? An empirical investigation. Vis. Sustainable. 19: 289-319 (**11 pages**).

Gunawan, Y.; Supriatna, N.K.; Firmansyah, A.I.; Slamet, S.; Wicaksono, N.A.; Ahadi, K.; Fadhilah, N.R., (2022). Endurance testing of the electric vehicle that converted from the internal combustion engine vehicle. Intl. J. Sustainable Transp. Technol., *5*(2): 61-69 (**9 pages**).

Habibie, A.; Hisjam, M.; Sutopo, W.; Nizam, M., (2021). Sustainability evaluation of internal combustion engine motorcycle to electric motorcycle conversion. Evergreen. 8(2): 469-476 (**8 pages**).

Hasudungan, A.; Waskito, A.S.; Banjaransari, A.; Sanjaya, A.; Ferlito, C.; Pramudya, E.P.; Gracelle, F.; Matthew, J.A.; Widjaja, N.; Casadio, P.; Ismail, R., (2023). Indonesia economic and business outlook 2023. Prasetiya Mulya Publishing, Jakarta.

Helmers, E. (2015). Possible Resource Restrictions for the Future Large-Scale Production of Electric Cars. In: Hartard, S., Liebert, W. (eds) Competition and Conflicts on Resource Use. Nat. Resour. Manage. Policy. 46. Springer.

Heylen, C.; Meunier, F.; Peeters, A.; Ek, S.; Neang, M.; Hean, S.; Peanh, S., (2020). Multidimensional benefits of sustainable agriculture practices of Cambodian smallholder farmers. Sustainable Agric. Res., 9(1):10-25 (**16 pages**).

Hout, M.C.; Papesh, M.H.; Goldinger, S.D., (2013). Multidimensional scaling, WIREs Cogn. Sci., (4): 93-103 **(11 pages)**.

Huang, X.; Lin, Y.; Lim, M.K.; Tseng, M.L.; Zhou, F., (2021). The influence of knowledge management on adoption intention of electric vehicles: perspective on technological knowledge. Industrial Manage. Data Syst., 121(7): 1481-1495 (**15 pages**).

Imansuri, F.; Wirandi, M.; Sumasto, F.; Aisyah, S.; Permana, A.K., (2023). Investment feasibility study of implementing electric conversion motorcycle in Indonesia: A sustainable development perspective. J. Ind. Services. 9(2): 81-86 (**6 pages**).

Karabelli, D.; Kiemel, S.; Singh, S.; Koller, J.; Ehrenberger, S.; Miehe, R.; Weeber, M.; Birke, K.P., (2020). Tackling xEV battery chemistry in view of raw material supply shortfalls. Frontiers in Energy Res., 8: 594857 (**13 pages**).

Kavanagh, P.; Pitcher, T.J., (2004). Implementing microsoft excel software for rapfish: A technique for the rapid appraisal of fisheries status. Fish. Center Res. Rep., 12(2): 1-75 **(75 pages)**.

Kenkel, N.C. and Orloci. L., (1986). Applying metric and nonmetric multidimensional scaling to ecological studies: some new results. Ecology. 67: 919–928 **(10 pages)**.

Kumar, R.R.; Alok, K., (2020). Adoption of electric vehicle: A literature review and prospects for sustainability, J. Cleaner Prod., 253: 119911 (**21 pages**).

Lomonova, E.A.; Vandenput, A.J.A.; Rubacek, J.; d'Herripon, B.; Roovers, G., (2002). Development of an improved electrically assisted bicycle. IEEE Industry Applications Conference. 37: 384-389 (**6 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**).

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).**

Ma, J.; Yang, D., (2024). Research on the mechanism of government-industry-university-research collaboration for cultivating innovative talent based on game theory. Heliyon. 10(3): 25335 (**20 pages**).

Martino, T.; Banister, D.; Bishop, J.D.K.; McCulloch, M., (2012). Realizing the Electric Vehicle Revolution. Nature Publishing Group, 2(5): 328-333 **(6 pages).**

Matasova, O.; Tupov, V., (2020). Calculation of the required noise reduction of a engine exhaust system. MATEC Web of Conferences. 320: 00017 (**9 pages**).

Neubauer, J.S.; Pesaran, A., (2013). A Techno-Economic Analysis of BEV Service Providers Offering Battery Swapping Services. National Renewable Energy Laboratory, Detroit, Michigan.

Novotny, A.; Szeberin, I.; Kovács, S.; Máté, D., (2022). National culture and the market development of battery electric vehicles in 21 countries. Energies. 15:1539 (**16 pages**).

Oryani, B.; Kamyab, H.; Moridian, A.; Azizi, Z.; Rezania, S.; Chelliapan, S., (2022). Does structural change boost the energy demand in a fossil fuel-driven economy? New evidence from Iran. Energy. 254: 124391 (**12 pages**).

Osatis, C.; Asavanirandorn, C., (2022). An exploring Human resource development in small and medium enterprises in response to electric vehicle industry development. World Electr. Veh. J., 13(6): 98 (**13 pages**).

Oyelaran-Oyeyinka, B.; Lal, K., (2006). Learning new technologies by small and medium enterprises in developing countries. Technovation. 26(2): 220-231 (**12 pages**).

Paczka, G.; Mazur-Pączka, A.; Garczyńska, M.; Kostecka, J.; Butt, K.R., (2021). Garlic (Allium sativum L.) Cultivation using vermicompost-amended soil as an aspect of sustainable plant product ion. Sustainability. 13(24): 13557 (**11 pages**).

Pipitone, E.; Caltabellotta, S.; Occhipinti, L., (2021). A life cycles environmental impact comparison between traditional, hybrid, and electric vehicles in the European context. Sustainability. 13(19): 10992 (**32 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).**

Proof, H.; Focjik, T., (2016). Pricing and commercialisation of electric mobility-dealing with high market uncertainty. Intl. J. Technol. Manage. 16(1): 30-54 **(25 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**).

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**).

Rohaeni, E.S.; Mailena, E.; Lesmayati, S.; Ermuna, S.S., (2021). Sustainability analysis for rice and duck farming in swampy land, Hulu Sungai Utara Regency, South Kalimantan. IOP Conf. Ser.: Earth Environ. Sci., 648: 012134 (**16 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. Plann., 19(2): 481-500 (**20 pages**).

Rubino, L.; Capasso, C.; Veneri, O., (2017). Review on plug-in electric vehicle charging architectures integrated with distributed energy sources for sustainable mobility. Appl. Energy. 207: 438– 464 (**27 pages**).

Sabyasachi, S.; Singh, A.R.; Godse, R.; Jaiswal, S.; Bajaj, M.; Srivastava, I.; Blazek, V.; Prokop, L.; Misak, S. (2024). Reimagining E-mobility: A holistic business model for the electric vehicle charging ecosystem. Alexandria Eng. J., 93: 236–258 (**23 pages**).

Sakunai, T.; Ito, L.; Tokai, A., (2021). Environmental impact assessment on production and material supply stages of lithium-ion batteries with increasing demands for electric vehicles. J. Material Cycles Waste Manage., 23: 470-479 (**10 pages**).

Salem, K.S.; Clayson, K.; Salas, M.; Haque, N.; Rao, R.; Agate, S.; Singh, A.; Levis, J.W.; Mittal, A.; Yarbrough, J.M.; Venditti, R.A., (2023). Critical review of existing and emerging technologies and systems to optimize solid waste management for feed-stocks and energy conversion. Matter. 6(10): 3348-3377 (**30 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).**

Sari, D.A.A.; Suryanto; Sudarwanto, A.S.; Nugraha, S.; Utomowati, R., (2021). Reduce marine debris policy in Indonesia. Earth Environ. Sci., 724(1): 012118 (**7 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**).

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**).

Suwignjo, P.; Yuniarto, M.N.; Nugraha, Y.U.; Desanti, A.F.; Sidharta, I.; Wiratno, S.E.; Yuwono, T., (2023). Benefits of electric motorcycle in improving personal sustainable economy: A view from Indonesia online ride-hailing rider. Intl. J. Technol., 14(1): 38-53 (**6 pages**).

Tchobanoglous, G.; Burton, F.L.; Stendel, H.D., (2014). Wastewater Engineering Treatment and Resource Recovery. 5 th Edition. New York: McGraw-Hill Education.

Ubaid, A.; Mazhar, A.R.; Riaz, Y.; Aziz, S.; Bhandari, K.S.; Jung, D.W., (2023). Development of an electric powertrain for the conversion of an ICE vehicle. International Conference on Metal Material Processes and Manufacturing. 44: 73-79 (**7 pages**).

Vacchi, M.; Siligardi, C.; Demaria, F.; Cedillo-González, E. I.; González-Sánchez, R.; Settembre-Blundo, D., (2021). Technological sustainability or sustainable technology? A multidimensional vision of sustainability in manufacturing. Sustainability. 13(17): 9942 (**18 pages**).

Veza, I.; Abas, M.A.; Djamari, D.W.; Tamaldin, N.; Endrasari, F.; Budiman, B.A.; Idris, M.; Opia, A.C.; Juangsa, F.B.; Aziz, M., (2022) Electric vehicles in Malaysia and Indonesia: Opportunities Challenges. Energies. 15(7):2564 (**24 pages**).

Wahyono, Y.; Irviandi, R.; Gilbran, A.; Panggabean, L.P.; Ridlo, R.; Sundari, S.; Suryaningtyas, A.D.; Prihatin, A.L.; Novianti, E.D.; Lestari, M.C.; Anisah, A. (2024). Study of carbon emissions in the use of fossil and renewable energy to Respond ro the urgency of a sustainable energy transition in Indonesia's group of twenty (G20) presidency: A short communication. In E3S Web of Conferences. 519: 03007 (**6 pages**).

World Resources Institute (WRI) Indonesia, 2023. Supporting Indonesia's achievement of net zero emissions target 2060, WRI Indonesia and the Ministry of Transportation Encourage Implementation of Land Transportation Climate Change Mitigation Action Strategy.

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**).

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**).

Zainol, Z.; Toha, S.F.; Kamisan, N.A.; Bukhari, W.M.S.W., (2019). Design and development of a retrofit electric motorbike. Intl. J. Recent Technol. Eng., 7(6):71–75 (**5 pages**).

Zhang, Y.; Ding, C., (2023). Using MDS preference plot as visual analytics of data: A machine learning approach. Methodol. Innovations. 16(1): 205979912211445 (**11 pages**).

Zainuri, F.; Tullah, F.H.; Prasetya, M.; Susanto, S.; Purnama, I.; Subarkah, D.; Ramiati, R.; Widiyatmoko, T.; Noval, R., (2023). Electric vehicle conversion study for sustainable transport. Recent in Eng. Sci. Technol., 1(02): 18–24 (**7 pages**).

Zhang, Q.; Zhu, X.; Lee, M.J., (2024). Exploring institutional pressures, green innovation, and sustainable performance: Examining the mediated moderation role of entrepreneurial orientation. Sustainability. 16(5): 2058 (**20 pages**).

AUTHOR (S) BIOSKETCHES

Santoso, A.D., Ph.D., Senior Researcher, 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/

Daulay, H., Dr., Senior Researcher at Research Center for Behavioral and Circular Economy, National Research and Innovation Agency, Indonesia.
- Email: *hotm001@brin.go.id*
- ORCID: 0000-0001-9664-5548
- Web of Science Researcher ID: HJP-7060-2023
- Scopus Author ID: 6506164078
- Homepage: https://brin.go.id/

Priyanti, A., Dr., Senior Researcher at Research Center for Behavioral and Circular Economy, National Research and Innovation Agency, Indonesia.
- Email: *atie001@brin.go.id*
- ORCID: 0000-0002-3503-5815
- Web of Science Researcher ID:D-6467-2013
- Scopus Author ID: 56315815700
- Homepage: https://brin.go.id/

Silalahi, M., Dr., Senior Researcher at Research Center for Behavioral and Circular Economy, National Research and Innovation Agency, Indonesia.
- Email: *vins001@brin.go.id*
- ORCID: 0000-0002-0171-0974
- Web of Science Researcher ID: NA
- Scopus Author ID: 56905441800
- Homepage: https://brin.go.id/

Yaumidin, U.K., Ph.D., Senior Researcher at Research Center for Behavioral and Circular Economy, National Research and Innovation Agency, Indonesia.
- Email: *umik001@brin.go.id*
- ORCID: 0000-0002-9345-6757
- Web of Science Researcher ID: J-5845-2015
- Scopus Author ID: 57215753909
- Homepage: https://brin.go.id/

Irawati, N., M.Si., Senior Researcher at Research Center for Transportation of Technology, National Research and Innovation Agency, Indonesia.
- Email: *novi.irawati@brin.go.id*
- ORCID: 0009-0006-0258-7724
- Web of Science Researcher ID: NA
- Scopus Author ID: 57523518500
- Homepage: https://brin.go.id/

Sumartono, H., M.T., Senior Researcher at Research Center for Transportation of Technology, National Research and Innovation Agency, Indonesia.
- Email: *hari012@brin.go.id*
- ORCID: 0000-0002-3339-0856
- Web of Science Researcher ID: NA
- Scopus Author ID: 58047046700
- Homepage: https://brin.go.id/

Astuti, P., M.M., Senior Researcher at Research Center for Agroindustry, National Research and Innovation Agency, Indonesia.
- Email: *puji003@brin.go.id*
- ORCID: 0009-0002-7257-1171
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

Parikesit, A., M.P., Junior Researcher at Research Center for Appropriate Technology, National Research and Innovation Agency, Indonesia.
- Email: *adji.parikesit@brin.go.id*
- ORCID: 0009000532556665
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

AUTHOR (S) BIOSKETCHES

Farandy, A.R., M.S., Junior Researcher at Research Center for Behavioral and Circular Economy, National Research and Innovation Agency, Indonesia.
- Email: *alan002@brin.go.id*
- ORCID: 0000-0002-8474-0967
- Web of Science Researcher ID: KUK-4120-2024
- Scopus Author ID: 57196286919
- Homepage: https://brin.go.id/

Manti, M.F., Dr., Assistant Deputy Coordinating Minister for Maritime and Transportation Industry, Coordinating Ministry for Maritime Affairs and Investment, Indonesia.
- Email: *bibilmanti@maritim.go.id*
- ORCID: 0009-0009-2381-6022
- Web of Science Researcher ID:
- Scopus Author ID: 6506164078
- Homepage: https://maritim.go.id/

Indriasari, E., M.Sc., Lecturer at Indonesian Land Transportation Polytechnic - Indonesian Land Transportation College, Ministry of Transportation, Indonesia.
- Email: *erlina_indriasari@dephub.go.id*
- ORCID: 0009-0000-7946-7014
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: http:// www.ptdisttd.ac.id

Joelijani, W., Dr., Deputy Secretary for Regional Research and Innovation, National Research and Innovation Agency, Indonesia., Indonesia.
- Email: *wiwi004@brin.go.id*
- ORCID: 0009-0000-2356-3656
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

Wahyuni, S., M.Sc., Senior Researcher at Research Center for Behavioral and Circular Economy, National Research and Innovation Agency, Indonesia.
- Email: *sriw025@brin.go.Id*
- ORCID: 0000-0002-5437-5356
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

HOW TO CITE THIS ARTICLE

Santoso, A.D.; Daulay, H.; Priyanti, A.; Silalahi, M.; Yaumidin, U.K.; Irawati, N.; Sumartono, H.; Astuti, P.; Parikesit, A.; Farandy, A.R.; 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.

DOI: 10.22034/gjesm.2024.10.SI.12

URL: https://doi.org/10.22034/GJESM.2024.SI.12

Global J. Environ. Sci. Manage. 10(SI): 201-218, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

A statistical approach to the water scarcity implications on food security

J. AlBtoosh[1], A. Abu-Awwad[2,*], N. Obeidat[3]

[1] *Waste Management Portfolio, Deutsche Gesellschaft fur Internationale Zusammenarbeit GmbH, Amman, Jordan*

[2] *Agricultural and Irrigation Engineering. Department of Land, Water and Environment, The University of Jordan, Amman 11942, Jordan*

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

ARTICLE INFO

Article History:
Received 20 March 2024
Revised 25 May 2024
Accepted 26 July 2024

Keywords:
Blended water
Crop water requirements
Freshwater
Regression model
Self-sufficiency

ABSTRACT

BACKGROUND AND OBJECTIVES: Jordan faces significant food security challenges due to population growth, climate change, and urbanization, straining limited water resources. Water supply expansion is constrained by economic and environmental factors, leading to a critical impact on agriculture, which stands as the largest consumer of water. The study emphasizes the crucial importance of regional water sources in ensuring food security, as the quantity and quality of irrigation water have a direct influence on crop yield and productivity. Managing irrigation is crucial for sustainability and livelihoods, given Jordan's reliance on food imports and climate change-induced production variability. This study delves into potato cultivation, examining the interconnections among irrigation water availability, crop yield, and self-reliance

METHODS: Irrigation with freshwater and blended treated wastewater in the middle and northern Jordan Valley is compared, using stepwise regression analysis and assuming other agricultural inputs to be optimal. Food security indicators, which include agricultural and socio-economic factors, along with water scarcity indicators, encompassing both water quantity and quality, were methodically chosen and examined.

FINDINGS: Regression analysis of potato production in Jordan revealed that increased blended water positively impacts yields, while higher water requirements and chloride levels negatively affect them. The negative implications of effective rainfall in combined water irrigation were evident, emphasizing the necessity for precise control over the levels of water quality and quantity. The study found that higher local potato production enhances self-sufficiency, crucial for food security. Enhanced water management techniques and advancements in agricultural practices have led to an increase in potato self-sufficiency, even in the face of dwindling water resources. Challenges from stable water requirements and decreasing rainfall can be addressed with advanced irrigation techniques and adaptive practices.

CONCLUSION: Improved water and crop management contribute to enhanced potato self-sufficiency in Jordan, despite varying water quality parameters. Furthermore, the results of research offer important information regarding the adjustment of potato cultivation to evolving climate patterns, including changes in precipitation temperature. These adaptation strategies can be shared and implemented in other countries facing similar climatic challenges.

DOI: 10.22034/gjesm.2024.10.SI.13

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

NUMBER OF REFERENCES
39

NUMBER OF FIGURES
8

NUMBER OF TABLES
3

*Corresponding Author:
Email: *abuawwad@ju.edu.jo*
Phone: +9627 9850 0018
ORCID: 0000-0001-8992-9518

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Jordan is confronted with significant food security obstacles as a result of swift population expansion, climate variability, and restricted water supplies. Economic and environmental constraints impact agricultural productivity, as agriculture is the largest global water consumer. Between 2000 and 2018, the population of Jordan experienced a significant increase from 5 million to 10 million individuals, with the influx of Syrian refugees playing a contributing role in this demographic growth (UN, 2024; FAO, 2020; Christoforidou *et al.,* 2022). Jordan's food security strategies involve either importing food or boosting local production. The 2008 global food price crisis highlighted the risks of heavy reliance on imports, leading to a renewed focus on self-sufficiency despite challenges like climate change and limited agricultural expansion (Smith *et al.,* 2019; Mrdalj and El Bilali, 2021). It is crucial to comprehend water use management in order to effectively tackle water scarcity. Freshwater is crucial for agricultural irrigation in Jordan, but its scarcity poses challenges for food security (Abu-Awwad, 2021; Mallareddy *et al*., 2023; Abu-Afifeh *et al*., 2023). Water management plays a critical role in agriculture, where the implementation of precision irrigation methods enhances both water conservation and crop productivity (Jiries *et al.,* 2010). The practice of blended water irrigation, which involves the combination of treated wastewater and freshwater, serves as an effective solution to address freshwater scarcity and enhance agricultural sustainability (MWI, 2023). Potatoes are a key crop in Jordan, making up 8.4 percent (%) of total production and covering 4,350 hectares (ha), with an annual yield of 167,000 tons (DOS, 2024). Wheat and barley are also important staples, alongside other crops like tomatoes and zucchini. Food security and water scarcity are urgent global issues. Food security depends on factors like food quantity, quality, availability, access, and socio-economic stability, as defined by the Food and Agriculture Organization (FAO) (Clapp *et al.,* 2022). Water scarcity arises due to a combination of economic, social, and ecological factors, exacerbated by challenges related to water quality issues, climate change, and pollution (Esmaeilion *et al*., 2021). The likelihood of future food shortages can be attributed to water scarcity, emphasizing the necessity of predictive models. By 2050, about 2.3 billion people may face severe water scarcity due to population growth and urbanization (Zhang *et al*., 2020). Data and models are instrumental in comprehending the effects of water scarcity on food security, providing valuable insights for the development of regional strategies (Nkiaka *et al*., 2021). This study examines statistical methods for water scarcity data, using benchmarks from food security data. The discussion focuses on new models utilizing adaptive filtering techniques, which are connected to food security in terms of efficiency and stability (Herman *et al*., 2020). The assessment concludes with practical recommendations and future steps (Nicholson *et al*., 2021). Stepwise regression is a method that chooses variables one by one based on the adjusted R-square value in order to predict a dependent variable. It involves forward selection and backward elimination to optimize the model. This has been shown to significantly enhance empirical prediction models in the fields of economics and agricultural economics (Sinaga and Darnius, 2023). Xiao *et al*. (2019) conducted a study on the water usage in agriculture in the Heihe River region of Northwest China, finding that it makes up 90% of the total water consumption. The analysis of crop incomes and water demands in Zhangye City was conducted by utilizing meteorological data and farmer surveys. The Crop water assessment tool (CROPWAT) model calculated the water needs of different crops, showing that seed corn, the most lucrative crop, and field corn required the highest amounts of water. The study advocated for seed corn and potato cultivation to balance economic returns and water conservation. Gabr (2021) used FAO-CROPWAT 8.0 and Climate Water Assessment Tool (CLIMWAT)-2.0 models with historical weather data from 1975 to 2014 to estimate water requirements for eight major irrigated crops in two agroecological regions in Egypt. This study highlighted the vital importance of local water resources in influencing food security, especially in Jordan. The quantity and quality of irrigation system water have a substantial effect on crop yield and productivity. Amirouche *et al*. (2023) examined agricultural water management in Algeria, focusing on water-intensive crops like potatoes. They used FAO's CROPWAT and AquaCrop models to estimate water requirements over 31 years in the semi-arid Wilaya of Tiaret. The robust relationship between the models' predictions underscored their dependability. AquaCrop's incorporation of factors

such as fertilization and salinity control provided extra advantages, improving irrigation techniques and boosting water efficiency and crop output. Gaddikeri *et al*. (2024) used CLIMWAT 2.0 and CROPWAT 8.0 to estimate crop evapotranspiration and create irrigation strategies tailored to the climatic conditions of six districts in Madhya Pradesh, India. The calculations unveiled notable differences in the water needs of various crops and districts. Effective irrigation management is essential for the sustainability of agriculture and the livelihoods of communities. Food production and economic stability are closely intertwined. In Jordan, a nation heavily dependent on food imports, the implementation of self-sufficiency measures is of utmost importance. This need is heightened by limited agricultural expansion and a growing population. Additionally, climate change also results in fluctuations in food production, highlighting the importance of implementing effective irrigation techniques to maintain stable crop harvests. Conducting long-term studies on the effects of water quantity and quality on potato production is crucial to understand the cumulative impacts of irrigation practices and climatic variability on crop yield. The development of tactics to maximize the usage of both freshwater and blended water in potato cultivation can effectively harmonize water efficiency and crop yield. Evaluating the socio-economic impact of different types of irrigation water can help farmers and policymakers make informed decisions. Additionally, investigating the impact of effective rainfall on water availability and potato production, while leveraging local knowledge systems, can improve the adoption of sustainable practices. Comparing irrigation practices between different regions and countries with similar challenges can identify best practices and innovative solutions adaptable to local conditions. The current study aims to investigate the correlation between irrigation water and potato crop yield in the context of food security through the utilization of stepwise regression analysis. This study has been carried out on the Jordan Valley in Jordan for the period of 2008-2023.

MATERIALS AND METHODS

The primary objective of this study is to examine the volume and standard of irrigation water utilized in the Jordan Valley (JV) for potato cultivation, a key crop in the region. More specifically, the condition of irrigation using BW in the middle part of the JV is considered, in comparison with irrigation using FW in the northern part of JV, assuming other agricultural production inputs and parameters to be optimal. Thus, the core focal points were quality of irrigation water from various sources, along with the water needs and productivity of potatoes in relation to food security in Jordan.

Study area description

The north and middle JV (Fig. 1), situated along the western border of Jordan, is a region characterized by its strategic location, distinct topography, varied climate, diverse crops, and critical water resources.

The JV stretches from the Sea of Galilee in the north to the dead sea in the south. The Northern JV is situated close to the Syrian borders, whereas the Central JV stretches southwards towards the heart of Jordan (Al-Husban and Ayen, 2020). This region forms part of the larger Jordan Rift Valley, which is a significant geographical feature in the Middle East. The JV is part of the Great Rift Valley system, renowned for its impressive and diverse topography. It features a mix of fertile plains, rolling hills, and steep escarpments. The valley is situated at a considerable distance below sea level, with heights dropping to as low as 400 meters (m) below sea level in the vicinity of the Dead Sea. This topography contributes to its unique microclimate and agricultural potential (Alhejoj and Salameh, 2023). The weather in the northern and central JV regions is mainly Mediterranean, with hot and dry summers, as well as mild and wet winters. The region experiences substantial variations in temperature and precipitation. Summers can see temperatures soaring above 40 degrees Celsius (°C), while winter temperatures are more moderate, typically ranging between 10 °C and 20 °C. The amount of rainfall experienced annually fluctuates across the region, with higher levels of precipitation observed in the northern territories in contrast to the southern regions. Typically, the annual rainfall falls within the range of 200 to 500 millimeters (mm). (Rodrigo-Comino, 2021). Its fertile soils and favorable climate conditions make the JV a prime agricultural zone. The region supports a wide variety of crops, including vegetables, citrus fruits, bananas, and dates. In the North JV, is known for cultivating common crops such as tomatoes, cucumbers, and peppers, while grapes and melons are also



Fig. 1: Geographic location of the study area in the Jordan Valley of Jordan (Salameh and Abdallat, 2020)

substantially cultivated in the Middle JV. These crops benefit from the valley's extended growing season and relatively stable climatic conditions (Ananda *et al*., 2020; Anbar *et al*., 2020). The agricultural productivity of the JV is heavily reliant on its water resources.. The region relies heavily on the Jordan River, which flows through the valley from the Sea of Galilee to the Dead Sea. Additionally, a multitude of springs and groundwater reservoirs play a crucial role in meeting the irrigation requirements of the valley. However, water scarcity remains a critical concern as a result of increased agricultural needs, agreements on water distribution among regions, and the effects of climate change. To mitigate these challenges, the use of treated wastewater for irrigation has become increasingly important, especially in the Middle JV, helping to sustain agricultural activities amidst limited fresh water irrigation (FW) availability (Almanaseer *et al*., 2020; Tawfik *et al*., 2023).

Stepwise regression analysis

Stepwise regression involves fitting regression models by automatically selecting predictive variables through a systematic procedure (Harrell, 2015). The objective was to pinpoint a subset of variables that held the most significance in forecasting the dependent variable. A correlation analysis was conducted to check for multicollinearity among the variables. The results revealed no significant multicollinearity concerns, as all correlation coefficients were well under the commonly accepted thresholds. Therefore, the econometric estimation had been proceeded with confidence in the independence of the variables. The general form of the multiple regression equation is shown in Eq. 1 (Harrell, 2015):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \qquad (1)$$

Where, Y is the dependent variable; β_0 is the variable intercept (e.g., crop yield); β_1, β_2,…, β_k are the coefficients of the independent variables; X_1, X_2,…, X_k are the independent variables (e.g., soil quality, rainfall, irrigation); and ε is the error term. In stepwise regression, involves the incremental inclusion or exclusion of variables from the model according to predetermined criteria, such as p-values derived from statistical tests (Harrell, 2015). The present study utilized forward selection as the stepwise regression technique to ascertain significant predictors. The initial model contained only the intercept. At each step, the predictor variable that resulted in the greatest increase in R-square value was added to the model. The selection process involved iterative evaluation of the R-square for all potential predictors at each stage, with the inclusion of the variable that contributed the most significant

enhancement to the model's fit. This forward selection continued until no remaining variables could significantly increase the R-square, ensuring that the final model included only those predictors that significantly contributed to explaining the variance in the dependent variable. The Augmented Dickey–Fuller (ADF) test serves the purpose of ascertaining the stationarity of a time-series, indicating the constancy of its statistical characteristics such as mean, variance, and autocorrelation over time. The ADF test is an extension of the Dickey-Fuller test and is used to test for a unit root in a time series sample. Stepwise regression, while useful for variable selection, has notable limitations. It can lead to overfitting, especially with small samples or many predictors, resulting in models that may not generalize well to new data. Additionally, the approach may generate unreliable models that are susceptible to slight data alterations and frequently fail to account for significant relationships between variables. Moreover, it neglects the integration of theoretical insights or previous studies, potentially resulting in the omission of crucial variables that align with established theories. These limitations indicate that while stepwise regression is valuable for exploratory analyses, it should be complemented with alternative techniques or theoretical perspectives for more robust Modeling (Sinaga and Darnius, 2023).

Water scarcity and food security indicators

Food security indicators, which include agricultural and socio-economic factors, and water scarcity indicators, which encompass both water quantity and quality, were methodically selected and analyzed. This comprehensive analysis aimed to understand the interplay between agricultural productivity, socio-economic conditions, and water availability and quality. The data spanning from 2008 to 2023 were gathered from various sources including the Department of Statistics (DOS), Ministry of Agriculture (MOA), Ministry of Water and Irrigation (MWI), and Jordan Valley Authority (JVA). Seasonal Decomposition using Time Series Analysis was employed to break down the observed time series into its trend, seasonal, and residual components. This technique enabled the detection of inherent patterns, seasonal fluctuations, and unpredictable variations in the dataset, leading to a holistic comprehension of the temporal dynamics. The area of land cultivated with potato and irrigated with FW in the JV (APFWJV) measures the extent of land relying on scarce FW resources for potato cultivation, which is crucial for understanding the strain on these resources. The area of land cultivated with potato and irrigated with BW in the JV (Fresh water irrigation) indicates a shift towards using BW for irrigation, reflecting adaptive strategies to cope with water scarcity. The cultivated potato land area in Jordan (CPJOR) serves as a fundamental metric for evaluating various irrigation methods. Additionally, potato production from FW-irrigated land in the JV (PPFWJV) assesses the productivity and efficiency of using FW, while potato production from blended water-irrigated land in the JV (PPBWJV) allows for evaluation of the effectiveness of BW irrigation on crop yield (Martínez-Valderrama *et al*., 2023). The population growth in Jordan (POPJOR) plays a crucial role as a socio-economic indicator, influencing the demand for food and exerting further pressure on water resources. The potato production rate from FW-irrigated land in the JV (PPRFWJV) measures the efficiency of FW usage in terms of production per area. Similarly, the potato production rate from blended water-irrigated land in the JV (PPRBWJV) demonstrates the productivity comparison associated with the use of BW. The overall potato production rate in Jordan (PPRJOR) provides a productivity metric across different irrigation methods, helping to gauge the broader implications of irrigation practices on food security (Al-Kharabsheh and Ta'any, 2005). Quantities of water supplied to lands cultivated with potato and irrigated with FW in the JV (QWSPFWJV) reflect the volume of FW dedicated to potato farming. In contrast, the quantities of water supplied to lands cultivated with potato and irrigated with BW in the JV (QWSPBWJV) measure the volume of BW used, which is important for resource allocation (Alkhaza'leh *et al*., 2023). Crop water requirements for potato in FW-irrigated land in the JV (CWRPFWJV) are essential for planning and ensuring an adequate water supply for optimal growth. Similarly, crop water requirements for potato in blended water-irrigated land in the JV (CWRPBWJV) provide insights into the water needs of crops under BW irrigation. Crop water requirements were estimated using the CROPWAT 8.0 and CLIMWAT models (free tools for calculating crop water and irrigation requirements provided by the FAO). All calculation procedures

Table 1: Water scarcity and food security indicators

Pilar	Description of the indicator	Unit	Code	Source
Agricultural	Area of land cultivated with potato and irrigated with FW in the JV	du	APFWJV	MOA, JVA
	Area of land cultivated with potato and irrigated with BW in the JV	du	APBWJV	MOA, JVA
	Area of land cultivated with potato in Jordan	du	APJOR	MOA, JVA
	Potato production from FW-irrigated land in the JV	ton	PPFWJV	MOA, JVA
	Potato production from BW-irrigated land in the JV	ton	PPBWJV	MOA, JVA
Socioeconomic	Population growth in Jordan	cap	POPJOR	DOS
	Potato production rate from FW-irrigated land in the JV	ton/du	PPRFWJV	MOA, JVA
	Potato production rate from BW-irrigated land in the JV	ton/du	PPRBWJV	MOA, JVA
	Potato production rate in Jordan	ton/du	PPRJOR	MOA, JVA
	Area of land cultivated with potato and irrigated with FW in the JV	du	APFWJV	MOA, JVA
	Area of land cultivated with potato and irrigated with BW in the JV	du	APBWJV	MOA, JVA
Water quantity	Quantities of water supplied to lands cultivated with potato and irrigated with FW in the JV	m3/du	QWSPFWJV	MWI, JVA
	Quantities of water supplied to lands cultivated with potato and irrigated with BW in the JV	m3/du	QWSPBWJV	MWI, JVA
	Crop water requirements for potato in FW-irrigated land in the JV	mm	CWRPFWJV	MWI, JVA
	Crop water requirements for potato in BW-irrigated land in the JV	mm	CWRPBWJV	MWI, JVA
	Effective rainfall in FW-irrigated land in the JV	mm	ERFWJV	MWI, JVA
	Effective rainfall in BW-irrigated land in the JV	mm	ERBWJV	MWI, JVA
Water quality	Salinity of water supplied to FW-irrigated land in the JV, measured by electrical conductivity	dS/m	ECFWJV	MWI, JVA
	Boron concentration in water supplied to FW-irrigated land in the JV	ppm	BOFWJV	MWI, JVA
	Chloride concentration in water supplied to FW-irrigated land in the JV	ppm	CLFWJV	MWI, JVA
	Salinity of water supplied to BW-irrigated land in the JV, measured by electrical conductivity	dS/m	ECBWJV	MWI, JVA
	Boron concentration in water supplied to BW-irrigated land in the JV	ppm	BOBWJV	MWI, JVA
	Chlorine concentration in water supplied to BW-irrigated land in the JV	ppm	CLBWJV	MWI, JVA

used in CROPWAT 8.0 were based on the two FAO publications of the Irrigation and drainage series, namely, No. 56 “Crop Evapotranspiration - Guidelines for computing crop water requirements” (Allen *et al*., 1998) and No. 33 titled “Yield response to water” (Doorenbos *et al*., 1980). The dates for the potato crop development stage required to run CROPWAT were set at 30 days. The way these dates changed over the period 2008-2023 involved cumulative data collection over the years; data were accumulated for each year incrementally (e.g., until 2008, then until 2009, and so on). For the FW irrigated lands, a rainfall and climate station was selected, whereas a different station was designated for the BW irrigated lands in the study. Effective rainfall in FW-irrigated land in the JV (ERFWJV) and in blended water-irrigated land (ERBWJV) indicate the natural water contribution, reducing the need for additional irrigation. Salinity of water supplied to FW-irrigated land in the JV, measured by electrical conductivity (ECFWJV), is a key water quality indicator, as high salinity can affect crop yield and soil health. Boron concentration in water supplied to FW-irrigated land (BOFWJV) must be managed to prevent toxicity in crops, whereas the concentration of chloride (CLFWJV) has a direct impact on plant growth and the usability of water. For blended water-irrigated land, salinity levels (ECBWJV), boron concentration (BOBWJV), and chlorine concentration (CLBWJV) are similarly critical for evaluating the suitability of BW for irrigation and its effects on crops (Abuzaid and Jahin, 2021; Alrbaihat and Abu-Afifeh, 2023). The combination of these indicators offers a thorough analysis of the relationship between food security and water scarcity (Table 1). Agricultural parameters emphasize the reliance on freshwater and the adjustment to using brackish water. Socio-economic metrics demonstrate the impact of population growth and productivity levels. Indicators related to water quantity and quality evaluate the effectiveness of water usage practices in terms of sustainability. These indicators signify the need for improved water management to maintain potato production in Jordan (PPJOR) and its self-sufficiency percentage (SSPJOR). The combination of these two components enables a comprehensive examination of agricultural sustainability and resource allocation,

Table 2. Statistics of variables used in the analysis over 2008-2023

Indicator	Unit	Statistics					Augmented Dickey-Fuller Test	
		Maximum	Minimum	Mean	Standard deviation	Coefficient of variation	Dickey-Fuller	p-value
APFWJV	du	10616	5510	7701	1438	19%	-2.4514	0.04004
APBWJV	du	19421	7706	12147	2833	23%	-2.7132	0.03022
APJOR	du	72558	34029	50646	12398	24%	-2.7092	0.03071
PPFWJV	ton	36829	17460	24967	5383	22%	-2.88654	0.02317
PPBWJV	ton	55516	24918	38737	9711	25%	-2.8982	0.02112
POPJOR	cap	11500000	6293000	9109813	1790401	20%	-2.488	0.03954
PPRFWJV	ton/du	4.3	2.2	3.4	0.70	21%	-2.6965	0.03193
PPRBWJV	ton/du	4.3	2.2	3.3	0.71	22%	-2.92442	0.01622
PPRJOR	ton/du	4.0	2.3	3.3	0.58	18%	-2.6644	0.03841
QWSPFWJV	m3/du	721	363	574	103	18%	-2.3976	0.04019
QWSPBWJV	m3/du	320	107	200	66	33%	-2.8035	0.02678
CWRPFWJV	mm	331	329	330	0.90	0%	-2.3345	0.04773
CWRPBWJV	mm	327	324	325	0.88	0%	-2.7996	0.0276
ERFWJV	mm	27.7	23.2	24.6	1.13	5%	-2.7781	0.02857
ERBWJV	mm	24.4	21.6	23.1	0.93	4%	-2.5219	0.03865
ECFWJV	dS/m	2.46	1.64	1.98	0.25	12%	-2.965	0.01495
BOFWJV	ppm	0.94	0.24	0.54	0.20	38%	-2.987	0.01259
CLFWJV	ppm	416	261	327	45	14%	-2.9692	0.01373
ECBWJV	dS/m	1.27	0.75	1.10	0.12	11%	-2.7642	0.03007
BOBWJV	ppm	0.30	0.02	0.17	0.08	44%	-2.8657	0.02339
CLBWJV	ppm	245	102	174	36	20%	-2.677	0.03736
PPJOR	ton	273906	103224	169637	40029	24%	-2.8386	0.02426
SSPJOR	%	98.6	62.1	86.0	9.1	11%	-2.4514	0.04004

providing direction for tactics aimed at harmonizing food output with limitations in water availability.

RESULTS AND DISCUSSION

Statistical analysis of water scarcity and food security indicators

The provided data are presented in Table 2, offering a comprehensive overview of key indicators relevant to potato cultivation in Jordan. The indicators are classified into different pillars including agriculture, socio-economic factors, water quantity, and water quality in the table, offering a comprehensive analysis that illuminates different facets of potato cultivation in the area. In the agricultural pillar, the data include crucial metrics such as the area of land cultivated with potatoes and corresponding production, for the period from 2008 to 2023. The JV showed a range of 5510 to 10,616 du for FW irrigation in the years 2022 and 2015, respectively, and 7706 to 19,421 du for BW irrigation in the years 2011 and 2014, respectively. Across Jordan overall, the cultivated land spans from 34,029 (2013) to 72,558 (2015) du. Potato production varies significantly, with FW irrigation in the JV yielding between 17,460 (2011) and 36,829 (2019) tons, and BW irrigation producing from 24,918 (2017) to 55,516 (2014) tons. The production rates in the JV exhibit a range of 2.2 to 4.3 tons per du, indicating disparities in irrigation techniques and farming methods. In the socio-economic pillar, the table highlights population growth in Jordan, ranging from approximately 6,293,000 (2008) to 11,500,000 (2023) caps, providing context for demographic trends that have impacted agricultural demands and resource management over a period of 16 years. The Water Quantity section provides a breakdown of the amount of water distributed per unit of cultivated land, specifically measured in dunums. In the JV, FW irrigation provides 363 (2022) to 721 (2011) cubic meter per dunum (m^3/du), while BW irrigation supplies 107 (2023) to 320 (2014) m^3/du. The data highlights the fluctuation in water accessibility and its essential impact on agricultural output. Water quality indicators such as electrical conductivity (EC), boron concentration, and chloride concentration are also presented, showing variability based on the type of irrigation used. This information is vital in evaluating the possible effects on the health and productivity of crops. The standard deviation (SD) and coefficient of variation (CV) are also essential statistical measures that offer deeper insights into the variability and relative variability of

key indicators related to potato cultivation in Jordan. The SD quantifies the spread of data points relative to the mean, illustrating the extent to which variables like potato yield and water volume deviate from their average levels. For instance, in potato production, SD values such as 5383 tons for FW-irrigated areas and 9711 tons for BW-irrigated areas indicate considerable variability in production levels, influenced by factors such as water availability and agricultural practices. Similarly, SD values for water quantities supplied to potato fields, such as 103 m^3/du for FW irrigation and 66 m^3/du for blended water irrigation, indicate how consistent the water supply is across different irrigation methods. Lower SD values indicate a water supply that is more stable and predictable, essential for ensuring crop yields. On the other hand, the CV provides a standardized measure of dispersion comparison to the mean. Comparing the variability across different datasets, while also taking into consideration their respective means, can be advantageous. For example, CV values of 21% for potato production rates in FW-irrigated areas and 22% in blended water-irrigated areas indicate their similar relative variability, despite slightly different mean production rates. Understanding the stability and potential risks linked to agricultural outputs under various irrigation conditions is crucial for gaining valuable insights. In terms of water quality, lower CV values for parameters such as electrical conductivity (EC) and boron concentration in both irrigation types (FW and BW) suggest more consistent water quality, which is critical for crop health and productivity. Regarding PPJOR, the data indicate significant fluctuations in potato production, from a minimum of 103,224 tons in 2013 to a maximum of 273,906 tons in 2016, with an average production of 169,637 tons. The substantial standard deviation of 40,029 tons suggests a significant degree of fluctuation in production quantities, potentially attributable to variables such as weather patterns, water accessibility, farming techniques, and market requirements. The CV (24%) reflects a moderate level of relative variability in potato production. Jordan's self-sufficiency percentage reflects the degree to which the country is able to fulfill its potato requirements through internal agricultural output. The self-sufficiency percentage ranges from a low of 62.1% in 2013 to a high of 98.6% in 2023, with an average of 86.0%. The 9.1% standard deviation implies a moderate level of variability, pointing towards the fact that Jordan is able to consistently fulfill a substantial part of its potato requirements through local farming practices. The CV (11%) confirms this low relative variability, signifying a stable level of self-sufficiency over time. The null hypothesis (H_0) of the ADF test posits that the time-series has a unit root, meaning that it is non-stationary (Harris, 1992). Conversely, the alternative hypothesis (H_1) posits that the time-series lacks a unit root and is thus considered stationary. A p-value less than 0.05 typically indicates that the null hypothesis can be rejected, suggesting that the time-series is stationary. Each of the indicators in the table supplied exhibits p-values below 0.05, enabling the rejection of the null hypothesis of a unit root for every series. Consequently, based on the outcomes of the ADF test, it can be concluded that each of these time-series exhibits stationarity. The statistical characteristics of these series, including measures like mean and variance, are shown to be consistent over time, allowing for the application of time-series analysis and modeling without the need for extra adjustments to ensure stationarity. Moreover, a significance level of $\alpha = 0.05$ was chosen for all statistical tests. It was found that all p-values obtained from the ADF test were significant.

These metrics are essential for policymakers and agricultural stakeholders in Jordan. The modest fluctuation in potato yield highlights the necessity for implementing measures to ensure stable production levels, such as enhancing agricultural techniques, optimizing water resources, and adjusting to changes in climate patterns (Jiries *et al.,* 2010; MWI, 2023). On the other hand, the relatively stable self-sufficiency percentage suggests that, despite fluctuations in production, Jordan can consistently meet a substantial portion of its potato demand through local cultivation, which is a positive indicator of food security.

Potato production dependency on water scarcity and food security indicators

Stepwise regression is a method for fitting regression models in which the choice of predictive variables is carried out through an automatic procedure. The evaluation of the relationship between potato production and water scarcity, as well as food security indicators, required a step-by-step process of including or excluding potential explanatory variables. This process was iteratively based on the coefficient of determination (R-square), adjusted R-squared, and p-value thresholds (Harrell, 2015). The dependent

Table 3. Analysis of variance for potato production (PPJOR)

Variable	Parameter Estimate	Standard Error	Type II SS	F-value	p-value
Intercept	148359206	32394209	6288850315	20.97	0.0018
PPRJOR	65859	9703	13812845968	46.07	0.0001
QWSPFWJV	142.6	74.9	1087645895	3.63	0.0933
QWSPBWJV	748.3	171.1	5737030102	19.13	0.0024
CWRPFWJV	-421408	91815	6316224497	21.07	0.0018
ERBWJV	-415788	92011	6122755598	20.42	0.002
CLBWJV	-661.8	146.8	6089846282	20.31	0.002
ECFWJV	165466	50268	3248631323	10.83	0.011

variable (Y) was Potato Production (PPJOR), while the independent variables (X) were the agricultural, socio-economic, and water quality and quantity indicators, as detailed in Eq. 2 (Harrell, 2015):

(2)

$$PPJOR = \beta_0 + \beta_1\ APFWJV + \beta_2\ APBWJV + \beta_3\ APJOR + \beta_4\ PPFWJV + \beta_5\ PPBWJV + \beta_6\ POPJOR + \beta_7\ PPRFWJV + \beta_8\ PPRBWJV + \beta_9\ PPRJOR + \beta_{10}\ QWSPFWJV + \beta_{11}\ QWSPBWJV + \beta_{12}\ CWRPFWJV + \beta_{13}\ CWRPBWJV + \beta_{14}\ ERFWJV + \beta_{15}\ ERBWJV + \beta_{16}\ ECFWJV + \beta_{17}\ BOFWJV + \beta_{18}\ CLFWJV + \beta_{19}\ ECBWJV + \beta_{20}\ BOBWJV + \beta_{21}\ CLBWJV$$

The provided Eq. 3 (Harrell, 2015) and Table 3 have been utilized to consolidate the findings of the stepwise regression analysis, specifically examining the correlation between PPJOR and different factors associated with water scarcity and food security. Each row presents a variable's parameter estimate, standard error, Type II sum of squares (SS), F-value, and p-value (Pr > F). None of the other variables reached the 0.1500 significance threshold for inclusion in the model. The model is outlined in the following section, along with a comprehensive analysis of the findings.

$$PPJOR = 148359206 + 65859\ PPRJOR + 142.6\ QWSPFWJV + 748.3\ QWSPBWJV - 421408\ CWRPFWJV - 415788\ ERBWJV - 661.8\ CLBWJV + 165466\ ECFWJV \quad (3)$$

The cultivation of potatoes in Jordan is significantly impacted by a range of factors, as emphasized through the statistical analyses. The potato production rate per dunum (PPRJOR) presented a robust impact on production quantities, with a parameter estimate of 65,859 and a highly significant F-value of 46.07 ($p < 0.0001$). It is evident that comprehending the fluctuations in potato yield per unit of land is essential in evaluating the level of potato self-sufficiency within the country. Factors such as soil fertility and agricultural practices influence this parameter. However, challenges associated with water supply management arise. While the quantity of water supplied through blended water irrigation (QWSPBWJV) was positively correlated with potato production, with an estimate of 748.3 and an F-value of 19.13 ($p = 0.0024$), freshwater irrigation (QWSPFWJV) showed less statistical significance (F-value of 3.63, $p = 0.0933$), suggesting a complex impact on overall water resource management. The combination of water irrigation is expected to improve potato yields as a result of its well-rounded nutrient composition and the potential for reduced salinity levels when compared to using solely freshwater irrigation. Water quantity plays a pivotal role in potato cultivation, yet it also poses challenges. Crop water requirements for freshwater-irrigated land (CWRPFWJV) and effective rainfall in blended water regions (ERBWJV) were both found to negatively impact potato production. CWRPFWJV, with a parameter estimate of −421,408 and an F-value of 21.07 ($p = 0.0018$), underscoring that higher water demands decrease production efficiency. Increased water demands for freshwater-irrigated areas may result in inefficiencies stemming from possible water scarcity and ineffective water management techniques, which can have a negative impact on the growth and productivity of crops. Similarly, ERBWJV, showing a parameter estimate of −415,788 and an F-value of 20.42 ($p = 0.002$), suggests that effective rainfall in blended water areas correlates with reduced potato yields. The efficient distribution of rainfall in blended water areas could potentially lead to improved soil moisture preservation and well-timed precipitation, ultimately enhancing the growth of crops. However, excessive rainfall can also lead to waterlogging and nutrient leaching, negatively impacting yields. Furthermore, various elements including inadequate irrigation timing resulting in either water scarcity or surplus, heightened soil salinity and contamination from processed wastewater, insufficient soil vaeration, and the existence of disease-causing agents or hazardous

substances in processed wastewater contribute to the issue. These factors collectively could stress the crops and reduce yields, thus justifying the research findings (Battikhi and Hill, 1986). The potato production landscape is additionally complicated by water quality parameters. Chloride concentration in blended water (CLBWJV) exhibited a significant negative relationship with potato yields, indicated by a parameter estimate of −661.8 and an F-value of 20.31 ($p = 0.002$). This statement highlights the adverse influence of increased chloride levels on the productivity of crops. Elevated chloride levels in blended water can increase soil salinity, leading to osmotic stress in plants, reduced nutrient uptake and, ultimately, lower yields. Conversely, the salinity of freshwater (ECFWJV), with a parameter estimate of 165,466 and an F-value of 10.83 ($p = 0.011$), unexpectedly showed a positive effect. The presence of elevated salinity levels in freshwater environments may imply the presence of naturally-occurring minerals that could potentially have a positive impact on the growth of potato plants. This could be attributed to an increase in nutrient availability or a decrease in competition from weeds and pests that are not well-adapted to saline conditions. In summary, Jordan's potato production is closely connected to the availability and quality of water resources within the region. While certain factors such as blended water irrigation show potential benefits, other factors such as high water demands and adverse water quality parameters present significant challenges. The optimization of management strategies is crucial in achieving a sustainable increase in potato production, all the while ensuring the preservation of water resources for upcoming agricultural demands. These findings aligned with Devaux (2014) who stated that the potato is vital to global food security and its importance is expected to grow. From 2020 to 2030, the potato's contribution to global food production is projected to rise from 3.74% to 6.42%, marking an increase of 2.68 percentage points. Potatoes play a crucial role as a staple crop due to their nutritional value and ability to thrive in various environmental conditions and soil types. Several factors threaten global food security. Population growth is anticipated to increase by 50% by 2050, leading to greater food demand. The planting regions conducive for agriculture are being altered by the increasing temperatures associated with climate change, consequently impacting the productivity of crops. Trade uncertainty, including restrictions and conflicts, poses risks to food security. Additionally, the COVID-19 pandemic has disrupted global food supply chains and driven up food prices.

Self-sufficiency percentage of potato dependency on water scarcity and food security indicators

The data presented in (Fig. 2) illustrates a clear upward trend in potato production in Jordan between 2008 and 2023, particularly highlighting notable spikes in 2011, 2014, and 2016. During these years, production levels reached as high as 216,483 tons in 2011, 204,084 tons in 2014, 273,906 tons in 2016, and 188,631 tons in 2023. Correspondingly, the self-reliance ratio of potatoes exhibited a consistent increase over the years, reaching a remarkable 98.6% in 2023. This overall increase suggests a positive correlation between time and potato production efficiency, likely due to improvements in agricultural practices, resource management, and possibly technological advancements in potato farming. Increased potato production is often associated with higher levels of self-sufficiency in many instances. In 2016, a total of 273,906 tons were produced, resulting in a self-sufficiency rate of 86.1%. Conversely, by 2023, the production quantity had decreased to 188,631 tons, yet achieving a record high self-sufficiency rate of 98.6%. This trend indicates that, as Jordan increases its potato production, it becomes more self-sufficient, reducing the need for imports and enhancing food security. On the other hand, during years characterized by decreased potato production, the corresponding self-sufficiency rates tend to decrease as well. To illustrate, in 2013, when the production hit a record low of 103,224 tons, the self-sufficiency percentage plummeted to 62.1%. This suggests that reduced production capacity directly impacts Jordan's ability to meet its potato consumption needs domestically, thereby lowering self-sufficiency. The prevailing tendency indicates that increased production typically results in greater self-reliance; however, certain years may diverge from this norm. In 2011, despite a high production of 216,483 tons, the self-sufficiency percentage was slightly lower, at 82.3%, compared to other high production years. Additionally, in 2017 and 2018, with moderate production levels (155,639 tons and 153,199 tons, respectively), the self-sufficiency percentages were quite high (at 93.1% and 91.4%, respectively). The irregularities indicate that self-sufficiency is influenced not only by production volumes, but also by factors like distribution efficiency, storage

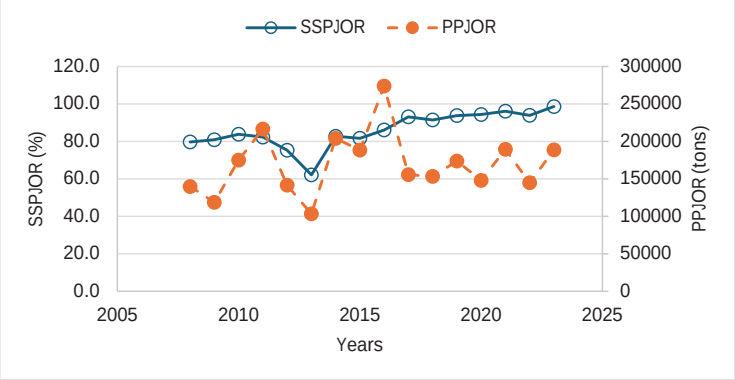


Fig. 2: Potato production in Jordan (PPJOR; tons) towards self-sufficiency percentage of potato in Jordan (SSPJOR; %)

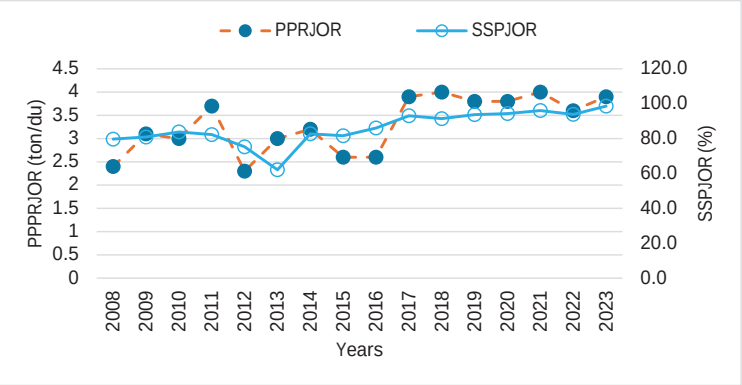


Fig. 3: Potato production rate in Jordan (PPRJOR; ton/du) towards self-sufficiency percentage of potato in Jordan (SSPJOR; %)

capabilities, and potential fluctuations in consumption patterns.

Fig. 3 illustrates the variations in the potato production rate (PPRJOR) throughout the years, displaying a clear upward trajectory in more recent years. For instance, production rates peaked in 2017 and 2018 at 3.9 and 4.0 tons per dunum, respectively, and maintained relatively high levels through to 2023. Correspondingly, the self-sufficiency percentage also presented a significant upward trend, peaking at 98.6% in 2023. The implication here is that increased production rates correlate with higher levels of self-sufficiency, underscoring the significance of enhancing productivity to attain food security. Higher potato production rates generally correlate with higher self-sufficiency percentages. In 2018, the self-sufficiency percentage reached 91.4% with a production rate of 4.0 tons per dunum. Similarly, in 2023, a production rate of 3.9 tons per dunum corresponded to the highest self-sufficiency percentage of 98.6%. Increasing the productivity per unit of land has the potential to greatly enhance Jordan's ability to meet its own potato production needs. In contras, years characterized by reduced production levels frequently exhibit diminished self-sufficiency percentages. In 2012, the production rate was at its lowest at 2.3 tons/du, resulting in a self-sufficiency percentage of 75.3%. The significance of production efficiency in fulfilling domestic demand and decreasing reliance on imports is highlighted by this trend. There are some deviations from this trend. For instance, in 2011, despite a high production rate of 3.7 tons/du, the self-sufficiency percentage was slightly lower (at 82.3%), compared to other high-production rate years. Similarly, in 2016, with a production rate of 2.6 tons/du, the self-sufficiency percentage was relatively high (at 86.1%). The irregularities indicate that self-sufficiency levels are influenced by factors beyond production rates, including domestic consumption

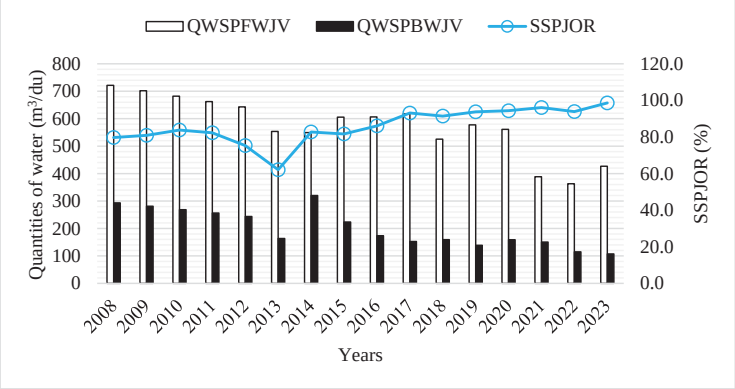


Fig. 4: Quantities of water supplied to freshwater irrigated lands (QWSPFWJV) and blended water irrigated lands (QWSPBWJV) in the Jordan Valley (m^3/du) towards self-sufficiency percentage of potato in Jordan (SSPJOR; %).

patterns, import-export dynamics, and potentially storage and distribution efficiencies.

Fig. 4 demonstrates a downward trend in the volume of water allocated for potato cultivation in the JV area between 2008 and 2023. Both FW irrigation (QWSPFWJV) and BW irrigation (QWSPBWJV) experienced a decrease over this timeframe. from 2008 to 2023, the quantities of water supplied for potato cultivation in the JV—both for FW irrigation (QWSPFWJV) and BW irrigation (QWSPBWJV)—generally decreased. FW irrigation levels fell from 721 m^3/du (in 2008) to 427 m^3/du (in 2023), while BW irrigation levels dropped from 293 m^3/du to 107 m^3/du over the same period. The self-sufficiency percentage displayed fluctuations despite the reductions, yet it demonstrated an increasing pattern, climbing from 79.7% in 2008 to a peak of 98.6% in 2023. The relationship between water supply and self-sufficiency reveals interesting insights. Despite the general reduction in FW supply, self-sufficiency has increased, suggesting that factors such as improved agricultural practices, better water management, and more efficient use of water resources might have played significant roles. In 2023, the minimum FW supply of 427 m3/du aligned with the maximum self-sufficiency percentage of 98.6%, suggesting a potential improvement in FW usage efficiency. Correspondingly, the reduction in BW availability was linked to a rise in self-reliance, indicating enhanced efficiency in utilizing BW for the growth of potatoes. High self-sufficiency percentages in 2021 and 2022, despite low BW supplies, further support this observation. Specific years provide a deeper understanding of these trends. In 2013, significant reductions in both FW (554 m^3/du) and BW (163 m^3/du) supplies were associated with the lowest self-sufficiency percentage of 62.1%, the lowest recorded at that time. t is clear from this that significant cuts in water resources can have a detrimental effect on self-sustainability, particularly in the absence of effective water conservation practices. Conversely, in 2021 and 2022, despite low water supplies (389 and 363 m^3/du for FW; 150 and 115 m^3/du for BW), self-sufficiency percentages were high (96.1% and 93.9%), suggesting that improved water management and agricultural practices have mitigated the negative impacts of reduced water supply. Jordan›s advancement in effectively utilizing scarce water resources to enhance self-reliance in potato production underscores the significance of of sustainable water management in agricultural productivity.

As shown in Figs. 5 and 6, the crop water requirements for potatoes in FW-irrigated land (CWRPFWJV) remained relatively stable from 2008 to 2023, fluctuating slightly between 329 mm and 331 mm. In contrast, effective rainfall on BW-irrigated land (ERBWJV) exhibited a downward trend, decreasing from 24.4 mm in 2008 to 21.6 mm in 2023. The self-reliance rate of potato production in Jordan experienced an overall growth, climbing from 79.7% in 2008 to 98.6% in 2023, despite fluctuations. The stability in crop water requirements (CWRPFWJV) suggests that this factor remained a consistent element in potato production. The self-sufficiency percentage did not experience any

significant adverse effects despite the minor rise from 329 mm to 331 mm. This implies that other factors, such as improved irrigation techniques and better crop management, may have played crucial roles in enhancing self-sufficiency. Conversely, the decrease in effective rainfall (ERBWJV) from 24.4 mm to 21.6 mm suggests a diminished supply of natural water for the cultivation of potatoes in BW-irrigated areas. However, the increase in self-sufficiency percentage during this period suggests that advances in water management practices and irrigation efficiency effectively mitigated the impact of reduced rainfall, demonstrating successful adaptation to changing water availability conditions. During certain years, significant fluctuations offer more comprehensive understanding. For instance, in 2013, the recorded precipitation was 23.1 mm and the crop water needs were 330 mm, aligning with the lowest self-sufficiency rate of 62.1%. This suggests that even slight increases in water requirements coupled with reduced rainfall can significantly affect production efficiency if not properly managed. Conversely, from 2017 onwards, the self-sufficiency percentage saw substantial growth, reaching 98.6% in 2023. During these years, crop water requirements were at their highest (331 mm), while effective rainfall was at its lowest (21.6 mm in 2023). During this era, the importance of enhanced water management and irrigation techniques in attaining a high level of self-sufficiency is emphasized, even in the presence of less than ideal natural water conditions. The information gathered during these years highlights the significance of employing adaptive agricultural techniques and optimizing water usage to support and improve potato cultivation in Jordan. As stated by Devaux (2014) water scarcity is a pressing issue, particularly in about 22 countries in North Africa and West Asia, with 15 of these already consuming more than their

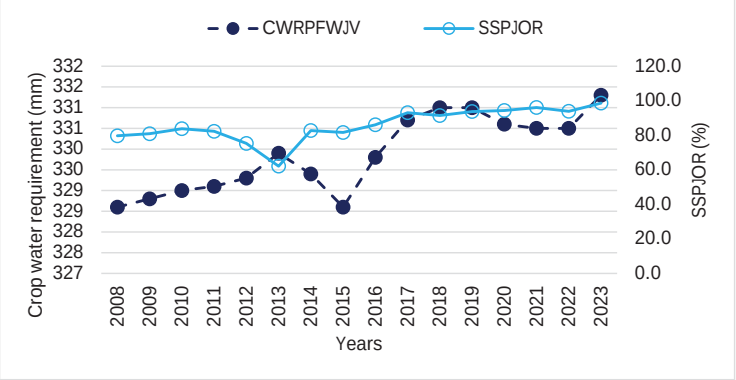


Fig. 5: Crop water requirement in freshwater irrigated lands in the Jordan Valley (CWRPFWJV; mm) towards self-sufficiency percentage of potato in Jordan (SSPJOR; %)

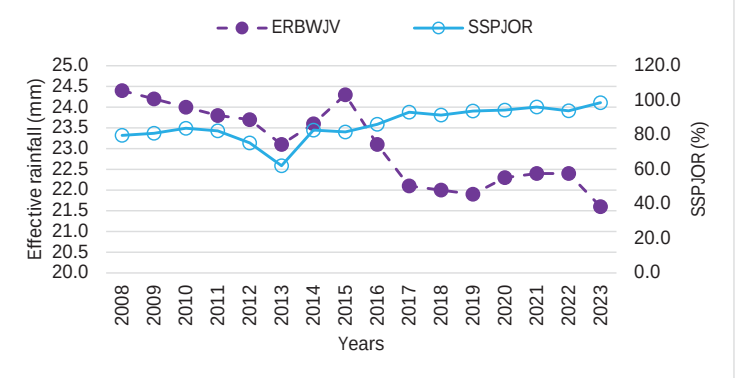


Fig. 6: Effective rainfall at the blended water irrigated lands in the Jordan Valley (ERBWJV; mm) towards self-sufficiency percentage of potato in Jordan (SSPJOR; %)

total renewable freshwater resources. Agricultural water efficiency in Africa is significantly lacking, as evidenced by a mere 3% utilization rate. This scarcity impacts potato production and other agricultural activities. Essential markers of food security encompass the frequency of malnourishment and the degrees of moderate or severe food insufficiency. These indicators have been updated through 2022 based on the latest data from the FAO.

As shown in Figs. 7 and 8, from 2008 to 2023, the electrical conductivity of FW (ECFWJV) used for irrigating potato crops in the JV fluctuated between 1.64 decisiemens per metre (dS/m) and 2.46 dS/m. The chloride levels in BW (CLBWJV) exhibited a notable degree of variation, with values ranging from 102 parts per million (ppm) to 245 ppm.. Over the same period, the self-sufficiency percentage of potato production in Jordan generally increased, starting at 79.7% in 2008 and reaching a peak of 98.6% in 2023.

The data indicates that there was no discernible pattern in the fluctuation of electrical conductivity in FW, while the self-sufficiency percentage of potato production exhibited a consistent increase over the years. Higher values of ECFWJV were observed in some years (e.g., 2.46 dS/m in 2008 and 2.42 dS/m in 2011) when the self-sufficiency percentage was lower, suggesting that higher salinity might negatively impact potato production. The chloride levels in BW (CLBWJV) exhibited a notable degree of variation, with values ranging. The variability of chloride concentration was

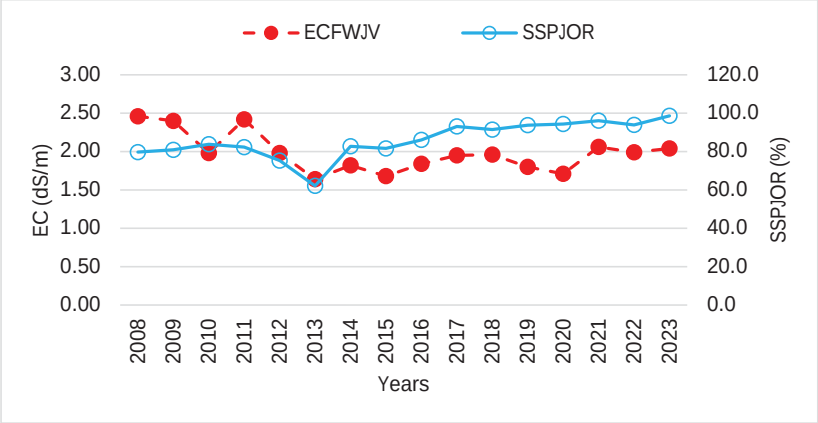


Fig. 7: Electrical conductivity of freshwater supplied for irrigation in the Jordan Valley (ECFWJV; dS/m) towards self-sufficiency percentage of potato in Jordan (SSPJOR; %).

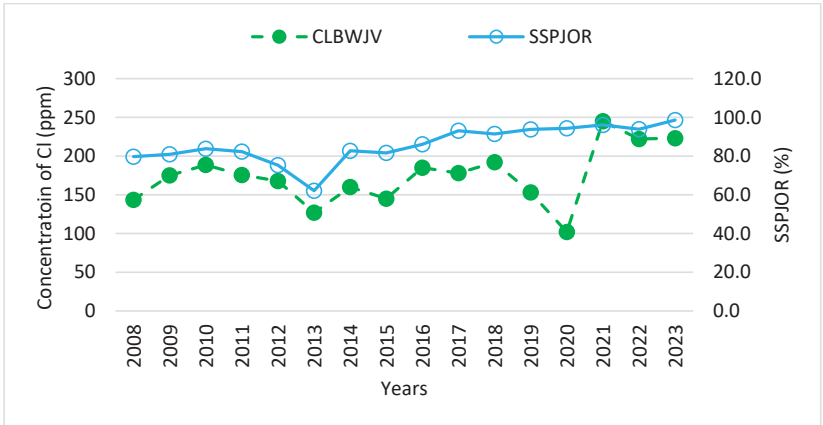


Fig. 8: Chloride concentration of the blended water supplied for irrigation in the Jordan Valley (CLBWJV; ppm) towards self-sufficiency percentage of potato in Jordan (SSPJOR; %)

more pronounced, as evidenced by significant spikes (for example, reaching 245 ppm in the year 2021). Despite these fluctuations, the self-sufficiency percentage rose significantly, indicating that potato production systems adapted to varying water quality levels. In years with lower chlorine concentrations (e.g., 127 ppm in 2013 and 102 ppm in 2020), the self-sufficiency percentage was either low or high, suggesting that other factors also play crucial roles in determining self-sufficiency beyond the chloride concentration alone. In 2013, the minimum electrical conductivity of FW was recorded at 1.64 dS/m, along with a relatively low chloride concentration of 127 ppm, which corresponded to the lowest self-sufficiency percentage of 62.1%. This suggests that, even with relatively good water quality, other factors significantly impacted self-sufficiency in that year. From 2017 onwards, the self-sufficiency percentage saw substantial growth—with peaks such as 98.6% in 2023—despite variations in both electrical conductivity and chloride concentration. In 2021, the self-sufficiency percentage was recorded at 96.1%, even with a high chloride concentration of 245 ppm. This indicates the effectiveness of improved agricultural practices, water management techniques and, perhaps, crop varieties more tolerant to salinity and chloride, which collectively enhanced self-sufficiency.

CONCLUSION

The regression analysis of potato production in Jordan identified several key factors influencing yields. The enhanced provision of mixed water had a beneficial influence on crop yields, while heightened crop water demands and increased chloride concentrations had an adverse impact. Additionally, effective rainfall in the context of blended water irrigation had a detrimental effect, highlighting the need to manage both water quality and quantity for optimal potato yieldsThe study revealed a direct relationship between increased domestic potato cultivation and the ability to meet one's own food needs, highlighting the importance of self-reliance in ensuring food security. However, factors such as import dynamics and consumption patterns also affect self-sufficiency, suggesting that productivity alone is not sufficient. Despite a decreasing water supply, improvements in water use and agricultural practices have enhanced potato self-sufficiency in Jordan. The stable water needs of crops and the decreasing amount of effective rainfall pose difficulties that may be mitigated by utilizing sophisticated irrigation methods and flexible strategies. Effective water and crop management have contributed to increased potato self-sufficiency, demonstrating the potential for better water use to improve food security. The research offers insights that could benefit other regions facing similar challenges, suggesting that optimized water management and agricultural practices can enhance potato yields and contribute to global food security. The results also offer significant information for adjusting potato cultivation to evolving climate circumstances and may direct global strategies and funding in the agricultural sector. Comparative studies with other regions could offer broader insights into potato production factors and foster international collaboration and knowledge exchange. However, this study focused on specific variables, including water quality parameters, potentially overlooking other factors like soil characteristics, pest management, and socio-economic variables. Moreover, depending on aggregated data could potentially lead to biases, making it challenging to generalize the findings to various crops or regions that have distinct agricultural methods and climate conditions. Additionally, the study underscores the significance of consistently monitoring and adapting agricultural practices in light of environmental shifts. Implementing advanced irrigation technologies and developing drought-resistant potato varieties could further bolster yield resilience. Cooperation with agricultural research institutions on a global scale has the potential to enhance the sharing of best practices and innovative ideas, thereby advancing sustainable potato farming practices worldwide.

AUTHOR CONTRIBUTIONS

A. Abu-Awwad, the corresponding author, has contributed in supervising the authors in analysing data, interpreting the results, and preparing the manuscript. J. Al-Btoosh prepared all the tables and figures and interpretation of the results. N. Obeidat participated in the interpretation of the results and manuscript preparation.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the University of Jordan, Amman, Jordan, for providing the resources and support necessary for

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

©2024 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
^{O}C	Degree Celsius
b_0	Variable intercept
ADF	Augmented Dickey–Fuller
AER	Agro-ecological regions
APBWJV	Area of land cultivated with potato and irrigated with BW in the JV
APFWJV	Area of land cultivated with potato and irrigated with FW in the JV
APJOR	Area of land cultivated with potato in Jordan
BOBWJV	Boron concentration in blended water-irrigated land
BOFWJV	Boron concentration in water supplied to FW-irrigated land
BW	Blended water irrigation
cap	Capita
CLBWJV	Chloride concentration in blended water
CLBWJV	Chlorine concentration in blended water-irrigated land
CLFWJV	Chloride concentration in water supplied to FW-irrigated land
CLIMWAT	Climate Water Assessment Tool
CROPWAT	Crop water assessment tool
CV	Coefficient of variation
CWR	Crop water requirements
CWRPBWJV	Crop water requirements for potato in blended water-irrigated land in the JV
CWRPFWJV	Crop water requirements for potato in FW-irrigated land in the JV
CWRPFWJV	Crop water requirements for FW-irrigated land
DOS	Department of Statistics
dS/m	Decisiemens per metre
du	Dunum
EC	Electrical conductivity
ECBWJV	Salinity levels in blended water-irrigated land
ECFWJV	Salinity of water supplied to FW-irrigated land in the JV
ECFWJV	Salinity of freshwater
Eq.	Equation
ERBWJV	Effective rainfall in blended water-irrigated land in JV
ERFWJV	Effective rainfall in fresh water-irrigated land in the JV
FAO	Food and Agriculture Organization
FW	Fresh water irrigation
ha	Hectare
H0	Null hypothesis
H1	Alternative hypothesis
IWR	Irrigation water requirements
JV	Jordan Valley

JVA	Jordan Valley Authority
m^3/du	Cubic meter per dunum
MENA	Middle East and North Africa
mm	Millimetre
MOA	Ministry of Agriculture
MWI	Ministry of Water and Irrigation
ppm	Part per million
POPJOR	Population growth in Jordan
PPBWJV	Potato production from BW-irrigated land in the JV
PPFWJV	Potato production from FW-irrigated land in the JV
PPJOR	Potato production in Jordan
ppm	Parts per million
PPRBWJV	Potato production rate from BW-irrigated land in the JV
PPRFWJV	Potato production rate from FW-irrigated land in the JV
PPRJOR	Potato production rate per dunum
QWSPBWJV	Quantities of water supplied to lands cultivated with potato and irrigated with BW in the JV
QWSPFWJV	Quantities of water supplied to lands cultivated with potato and irrigated with FW in the JV
SD	Standard deviation
SS	Sum of squares
SSPJOR	Self-sufficiency percentage of potato in Jordan
ton	Ton
ton/du	Ton per dunum
X	Independent variables
Y	Dependent variable

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. 15(23): 16239 (**19 pages**).

Abu-Awwad, A.M., (2021). Wastewater treatment and its reuse in Jordan. Jordan J. Agric. Sci., 17(3): 211–223 (**12 pages**).

Abuzaid, A.; Jahin, H., (2021). Changes in alluvial soil quality under long-term irrigation with two marginal water sources in an arid environment. Egypt. J. Soil Sci., 61(1): 71–80 (**10 pages**).

Alhejoj, I.; Salameh, E., (2023). An introduction to the geology of Jordan. Cambridge Scholars Publishing, UK.

Al-Husban, Y.; Ayen, A., (2020). The impact of the syrian civil war on land use / land cover in Al-Yarmouk basin during 2010–2018. Geogr. Environ. Sustainability. 13(2): 147–153 (**7 pages**).

Al-Kharabsheh, A.; Ta'any, R., (2005). Challenges of water demand management in Jordan. Water Int., 30: 210–219 (**10 pages**).

Alkhaza'leh, H.; Abu-Awwad, A.; Alqinna, M., (2023). Effect of irrigation with treated wastewater on potatoes' yields, soil chemical, physical and microbial properties. Jordan Earth Environ. Sci., 14(2): 135–145 (**11 pages**).

Allen, R.G.; Pereira, L.; Raes,, D.; Smith, M., (1998) Crop evapotranspiration: guidelines for computing crop water requirements; food and agriculture organization of the United Nations, Rome.

Almanaseer, N.; Hindiyeh, M.; Al-Assaf, R., (2020). Hydrological and environmental impact of wastewater treatment and reuse on Zarqa river basin in Jordan. Environvironments. 7(2): 1-14 (**14 pages**).

Alrbaihat, M.R.; Abu-Afifeh, Q., (2023). Eco-friendly microplastic removal through physical and chemical techniques: a review. Ann. Adv. Chem., 7: 14-24 **(11 pages).**

Amirouche, M.; Smadhi, D.; Zella, L., (2023). Modelling of water use efficiency using CropWat and AquaCrop : case of potato in semi-arid region. Al-Qadisiyah J. Agric. Sci., 13(1): 50–58 (**9 pages**).

Ananda, G.K.S.; Myrans, H.; Norton, S.L.; Gleadow, R.; Furtado, A.; Henry, R.J., (2020). Wild sorghum as a promising resource for crop improvement. Front. Plant Sci., 11: 1-14 (**14 pages**).

Anbar, A.; Abu-Dalhoum, M.; Maslamani, A.; Al-Antary, T.; Sawwan, J., (2020). Agricultural patterns in Jordan: a new analytical approach. Fresenius Environ. Bull., 29: 10980–10996 (**17 pages**).

Battikhi, A.M.; Hill, R.W., (1986). Irrigation scheduling and watermelon yield model for the Jordan Valley. J. Agron. Crop Sci., 157: 145–155 (**11 pages**).

Christoforidou, M.; Borghuis, G.; Seijger, C.; van Halsema, G.E.; Hellegers, P., (2022). Food security under water scarcity: a comparative analysis of Egypt and Jordan. Food Secur., 15: 171-185 (**15 pages**).

Clapp, J.; Moseley, W.G.; Burlingame, B.; Termine, P., (2021). The Case for a Six-Dimensional Food Security Framework. Food Policy. 106: 1–10 (**10 pages**).

Devaux, A.; Kromann, P.; Ortiz, O., (2014). Potatoes for Sustainable Global Food Security. Potato Res., 57: 185–199 (**14 pages**).

Doorenbos, J.; Kassam, A.H.; Bentvelsen, C.; Uittenbogaard, G., (1980). Yield response to water. Irrig. Agric. Dev., 257–280 (**24 pages**).

DOS, (2023). Area and production rate of vegetable crops., (Accessed 20 April 2024).

Esmaeilion, F.; Ahmadi, A.; Hoseinzadeh, S.; Aliehyaei, M.; Makkeh, S.A.; Astiaso Garcia, D., (2021). Renewable Energy Desalination; a Sustainable Approach for Water Scarcity in Arid Lands. Int. J. Sustainable Eng., 14: 1–27 (**27 pages**).

FAO, (2020). The state of food and agriculture 2020; FAO.

Gabr, M.Els., (2021). Modelling net irrigation water requirements using fao-cropwat 8.0 and climwat 2.0: a case study of tina plain and east south ElKantara regions, North Sinai, Egypt. Arch. Agron. Soil Sci., 68: 1322–1337 (**16 pages**).

Gaddikeri, V.; Rajput, J.; Dimple, N.; Singh Jatav, M.; Kumari, A.; Rana, L.; Rai, A.; Gangwar, A., (2024). Estimating crop water requirement in Madhya Pradesh's agro-climatic regions: A cropwat and climwat software case study. Environ. Conserv. J., 25: 308–326 (**19 pages**).

Harrell, F.E., (2015). Regression modeling strategies; 2nd ed.; Springer Science & Business Media. New York, Springer.

Harris, R.I.D., (1992). Testing for unit roots using the augmented dickey-fuller test. Econ. Lett., 38: 381–386 **(6 pages).**

Herman, J.D.; Quinn, J.D.; Steinschneider, S.; Giuliani, M.; Fletcher, S., (2020). Climate Adaptation as a Control Problem: Review

and Perspectives on Dynamic Water Resources Planning under Uncertainty. Water Resour. Res., 56: 1-32 (**32 pages**).
Jiries, A.; Ta'any, R.; Abbassi, B.; Oroud, I., (2010). Agriculture water use efficiency in Wadi Shu'eib area, Jordan. Pol. J. Environ. Stud., 19(2): 337–341 **(5 pages).**
Mallareddy, M.; Thirumalaikumar, R.; Balasubramanian, P.; Naseeruddin, R.; Nithya, N.; Mariadoss, A.; Eazhilkrishna, N.; Choudhary, A.K.; Deiveegan, M.; Subramanian, E.; Padmaja, B.; Vijayakumar, S., (2023). Maximizing water use efficiency in rice farming: a comprehensive review of innovative irrigation management technologies. Water. 15(10): 1-28 **(28 pages).**
Martínez-Valderrama, J.; Olcina, J.; Delacámara, G.; Guirado, E.; Maestre, F.T., (2023). Complex policy mixes are needed to cope with agricultural water demands under climate change. Water Resour. Manage., 37: 2805-2834 (**30 pages**).
Mrdalj, V.; El Bilali, H., (2021). Agri-food markets, trade, and food and nutrition security, 2021: 87–106 (**20 pages**).
MWI, (2023). National water strategy 2023 – 2040; the ministry of water and irrigation, Amman, Jordan.
Nicholson, C.F.; Stephens, E.C.; Kopainsky, B.; Jones, A.D.; Parsons, D.; Garrett, J., (2021). Food Security Outcomes in Agricultural Systems Models: Current Status and Recommended Improvements. Agric. Syst., 188: 1-28 (**28 pages**).
Nkiaka, E.; Okpara, U.T.; Okumah, M., (2021). Food-Energy-Water Security in Sub-Saharan Africa: Quantitative and Spatial Assessments Using an Indicator-Based Approach. Environ. Dev., 40: 1-13 (13 pages).
Rodrigo-Comino, J.; Salvia, R.; Quaranta, G.; Cudlín, P.; Salvati, L.; Gimenez-Morera, A., (2021). Climate aridity and the geographical shift of olive trees in a mediterranean northern region. Climate. 9: 1-17 (**17 pages**).
Salameh, E.; Abdallat, G., (2020). Potential areas for managed aquifer recharge in the eastern lower Jordan Valley area. J. Water Resour. Prot., 12: 330–357 (**28 pages**).
Sinaga, R.; Darnius, O., (2023). Binary logistic regression analysis using stepwise method on tuberculosis events. J. Math. Educ. Appl., 2(1): 1–10 (**10 pages**).
Smith, V.H.; Glauber, J.W., (2019). Trade, policy, and food security. Agric. Econ., 51: 159–171 (**13 pages**).
Tawfik, M.H.; Al-Zawaidah, H.; Hoogesteger, J.; Al-Zu'bi, M.; Hellegers, P.; Mateo-Sagasta, J.; Elmahdi, A., (2023). Shifting waters: the challenges of transitioning from freshwater to treated wastewater irrigation in the northern Jordan Valley. Water. 15(7): 1-16 (**16 pages**).
UN, (2024). The 17 sustainable development goals.
Woertz, E., (2017). Agriculture and development in the wake of the arab spring. Revue internationale de politique de développement. 7(2017): 1-7 (**7 pages**).
Xiao, X.; Fan, L.; Li, X.; Tan, M.; Jiang, T.; Zheng, L.; Jiang, F., (2019). Water use efficiency of crops in the arid area of the middle reaches of the Heihe River: Taking Zhangye city as an example. Water. 11(8): 1-12 (**12 pages**).
Zhang, D.; Sial, M.S.; Ahmad, N.; Filipe, A.J.; Thu, P.A.; Zia-Ud-Din, M.; Caleiro, A.B., (2020). Water Scarcity and Sustainability in an Emerging Economy: A Management Perspective for Future. Sustainability. 13: 1-10 (**10 pages**).

AUTHOR (S) BIOSKETCHES

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

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

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: NA
- Scopus Author ID: NA
- Homepage: https://agriculture.ju.edu.jo/Home.aspx

HOW TO CITE THIS ARTICLE

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(SI): 201-218.

DOI: 10.22034/gjesm.2024.10.SI.13

URL: https://www.gjesm.net/article_714637.html

Global J. Environ. Sci. Manage. 10(SI): 219-236, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Exploring the potential of palm oil plantation waste for local communities using mixed methods

A. Ilhami, T. Hidayat*, Riandi

Faculty of Mathematics and Natural Science Education, Universitas Pendidikan Indonesia, Indonesia

ARTICLE INFO

Article History:
Received 19 March 2024
Revised 21 May 2024
Accepted 24 July 2024

Keywords:
Agriculture
Local community
Palm oil
Riau
Waste

ABSTRACT

BACKGROUND AND OBJECTIVES: Riau is Indonesia's largest palm oil supplier region, part of which is managed by smallholder farmers. The escalation in the worldwide need for palm oil has resulted in the expansion of plantations, consequently causing a rise in palm oil waste. Small-scale farmers lack sufficient knowledge and resources for waste management. The study aims to estimate and forecast the volume of palm oil waste generated and the utilization inventory by indigenous populations in Riau province.

METHODS: The present study employs a combination of quantitative and qualitative methodologies. Utilizing secondary data obtained from the Central Statistics Agency, the research calculates the volume of waste generated by smallholder oil palm plantations and forecasts the quantity of palm oil waste. The prediction method uses the time series modeler method with the help of a statistical package for the social sciences 23. Subsequently, surveys were employed to gather quantitative information regarding the utilization of palm oil waste by indigenous populations in the province of Riau. The respondents involved were 112 people using the convenience sampling method. Descriptive statistics are utilized in data analysis to determine the quantity of waste and to gain insight into the local population's utilization. Interviews were also conducted with seven local people who work as farmers regarding the management and use of palm oil waste. Interview data were analyzed using descriptive qualitative methods.

FINDINGS: Analysis of smallholder plantation waste in Riau shows that the most significant type is stem parts at 82 percent. Palm oil waste will increase to 236.37 million tons in the next decade. Approximately 80 percent of local communities handle plantation waste by depositing it on plantations for natural decomposition.

CONCLUSION: The amount of smallholder plantation waste is enormous and will continue to increase. It is crucial to prioritize the improvement of waste management standards at the local community level in order to promote the sustainability of palm oil plantations. The findings significantly contribute to promoting sustainable environmental management, providing actionable insights for policymakers and environmental activists.

DOI: 10.22034/gjesm.2024.10.SI.14

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
8

NUMBER OF TABLES
4

*Corresponding Author:
Email: *topikhidayat@upi.edu*
Phone: +8180 900 7036
ORCID: 0000-0002-4589-8059

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Palm oil is derived from the fruit of the oil palm tree (*Elaeis guineensis Jacq*.), a species that thrives in tropical regions. Oil palm grows well in tropical rainforest areas with an annual rainfall of 1780–2280 milimeter (mm) and an environmental temperature interval of 24–30 degrees Celsius (℃) (Urugo *et al.,* 2021). Indonesia is a country that has more than 80 percent (%) of tropical rainforest in Southeast Asia (Indrajaya *et al.,* 2022), making it suitable for oil palm plantations (Petrenko *et al.,* 2016). Xu *et al*. (2022) stated that forested land cover decreased due to the expansion of oil palm plantations. Since its initial introduction in 1911, this plant has made substantial progress in Indonesia, evolving into a key commodity by 1970 (Hambali and Rivai, 2017). The process of establishing oil palm plantations commences with the clearance of land designated for cultivation. This involves the utilization of heavy machinery, logs, and controlled burning techniques by individuals involved in the industry. Oil palm seedlings are planted in polybags for 10–12 months in a nursery (Rosenani *et al*., 2016) and then planted at a density of approximately 150 palm trees/hectare (ha) (Woittiez *et al*., 2017). The maturation period for oil palm trees is approximately three years, during which they generate a one fresh fruit bunch (FFB) every 10–21 days (Lai *et al*., 2023). The development of palm fruit until maturity takes approximately 180 days (Romero *et al*., 2021). Oil palm plants are replanted when they are 25–30 years old because of the complex harvesting process (Woittiez *et al*., 2017). Indonesia is the leading producer of palm oil globally, with oil palm plantations spanning 26 provinces, particularly concentrated in Sumatra, Kalimantan, parts of Sulawesi, and Papua (BPS, 2022b). The amount of palm oil supplied exceeds 85% of the global supply, and is the world's leading market supplier of vegetable oils (Petrenko *et al*., 2016). Indonesia supplied 42.5 million tons of palm oil in 2020. The prevalence of this dominance is closely linked to the extensive expanse of oil palm plantations, spanning 16.38 million hectares, and the substantial production output of 54.3 million tons in the year 2022. The optimal tropical weather conditions are conducive for the growth of oil palm plantations. High rainfall and sufficient sunlight support the optimization of oil palm growth. Significant assistance has been extended by the Indonesian government to the palm oil sector through various means such as subsidies, incentives, and regulatory frameworks that promote industrial advancement (Murphy *et al*., 2021). The government focuses more on calculating crude palm oil (CPO) production and pays less attention to the amount of waste produced. Riau Province is the region with the largest palm oil supplier in Indonesia. Riau has been designated as a center for palm oil production and has become a barometer in the palm oil industry in Indonesia. The recorded oil palm plantation area in this region is 3.38 million hectares, representing 20.68% of the total oil palm plantation area in Indonesia (Raharja *et al*., 2020). In 2022, Riau province will have an area of 2.87 million ha or 18.70 % of the total area of oil palm plantations in Indonesia. Meanwhile, community-managed oil palm plantations reach 1.7 million ha (BPS, 2022b). Palm oil plantation commodities play a significant role in the economic activities of Riau due to their high potential for palm oil production in the industrial sector. The most significant CPO production in 2022 will come from Riau Province, with production of 8.74 million tons or around 18.67% of Indonesia's total production, which is supplied from smallholder plantations (55.13%), state plantations (4.5%) and private plantations (40.36%) (BPS, 2022b). The escalation in global palm oil demand has resulted in the increased expansion of palm oil plantations worldwide. The government is essential in supporting farmers to realize sustainable palm oil plantations (Cifuentes-Espinosa *et al*., 2023). Government efforts should mainstream the commitment to implementing RSPO certification in order to increase crop yields (Hassan *et al*., 2024) and environmental issues (Rodthong *et al*., 2023). The large amount of palm biomass produced includes empty fruit bunches (EFB), palm kernel shells, mesocarp fiber, palm oil mill effluent (POME), stems, and leaves. Improper management of palm oil plantation waste can negatively impact the environment, such as water, soil, and air pollution. This can endanger human health (Ayompe *et al*., 2021), disrupt ecosystems (Teng *et al*., 2020) and climate change (Ahmed *et al*., 2021). This study has the potential to make a substantial impact on the development of palm oil waste management strategies in Riau Province. This research is the first research to specifically investigate oil palm waste by smallholder plantations in Riau Province by applying a mixed-method approach. The

study conducts an analysis and forecasts the quantity of oil palm residue produced by small-scale farms, while also gathering information on the utilization of palm oil waste by individuals. The results of previous research regarding the assessment of oil palm plantations in Riau include the formulation of institutional strategies for oil palm cultivation to improve the economy of local communities (Syahza and Asmit, 2020), gender analysis in the management of oil palm plantations (Retnaningsih *et al.,* 2022), analysis of ownership conflicts in oil palm plantation land (Manurung *et al.,* 2021), appropriate technology for processing palm oil waste biomass for the community (Nasution *et al.,* 2021). The current emphasis of the government remains on the enhancement of the extensive palm oil sector. Waste management in oil palm plantations overseen by governmental bodies and private entities is well-equipped, however, it lacks provisions for small-scale farmers. The farmers need more knowledge and skills in managing waste. A significant increase in waste will impact environmental quality. Enhancing the oil palm plantation within the economic sphere necessitates a comprehensive evaluation of its social and environmental implications. Palm oil waste still receives little attention in smallholder plantations, even though it is crucial for the sustainability of palm oil plantations in the future. It is crucial to examine how smallholder farmers utilize palm oil waste, especially given their limited understanding of plantation management and access to advanced technological resources in comparison to state and private sector management. The main waste of small farmers is stems and leaves, which have commercial potential and could be used to make them more valuable (Pulingam *et al.,* 2022). Smallholders in Riau Province possess 55.13% of the total oil palm plantation area (BPS, 2022b). Independent smallholders manage almost half of the total land, whose contribution to total palm oil production in Indonesia ranges between 27% and 38% (Raharja *et al.,* 2020). The aim of study to quantify the volume of palm oil waste generated by smallholder oil palm plantations, forecast its accumulation over the course of several decades, and assess the extent of the Riau community's understanding ofits utilization. This study was carried out in Riau province, Indonesia, in 2024.

MATERIALS AND METHODS

The study area

The research used a mixed-method explanatory design. The method was specifically chosen so that the problem of potential oil palm plantation waste at the research location could be explained well and in detail. This study design integrates both quantitative and qualitative methods of data gathering and analysis to provide a comprehensive understanding of a particular phenomenon (Creswell and Guetterman, 2019). This study was conducted in Riau Province, Indonesia, as presented in Fig. 1.

This study follows the research stages of Creswell and Guetterman (2019), encompassing the following procedures; i) first collecting quantitative data; ii) quantitative data analysis; iii) gathering qualitative data based on quantitative data findings; iv) collecting qualitative data; v) interpreting quantitative data through qualitative findings. The rationale behind this method is that quantitative data outcomes offer a broad overview of the research issue. Additional examination using qualitative data gathering may elucidate the overall context of quantitative data. Quantitative data consists of calculating the amount of waste using secondary data from the Central Statistics Agency (BPS) and inventorying the use of palm oil waste by local communities. The waste utilization survey used a questionnaire. Descriptive statistics were employed to analyze the questionnaires and calculate the volume of palm oil waste. Qualitative data collection was interviews with small oil palm farmers. Observations on oil palm plantations were also carried out to obtain empirical data and directly observe farmers' activities. Descriptive-qualitative analysis was conducted on the results obtained from interviews and observations. The interpretation of interviews and observations conducted in the field can provide insights into the quantitative data findings.. These steps are explained through a flowchart in Fig.2

Data collection

The study gathers numerical information by utilizing surveys to catalog the expertise of the local community in managing palm oil waste. The number of respondents involved in the research was 112 people using the convenience sampling method. The instrument indicators encompass familiarity

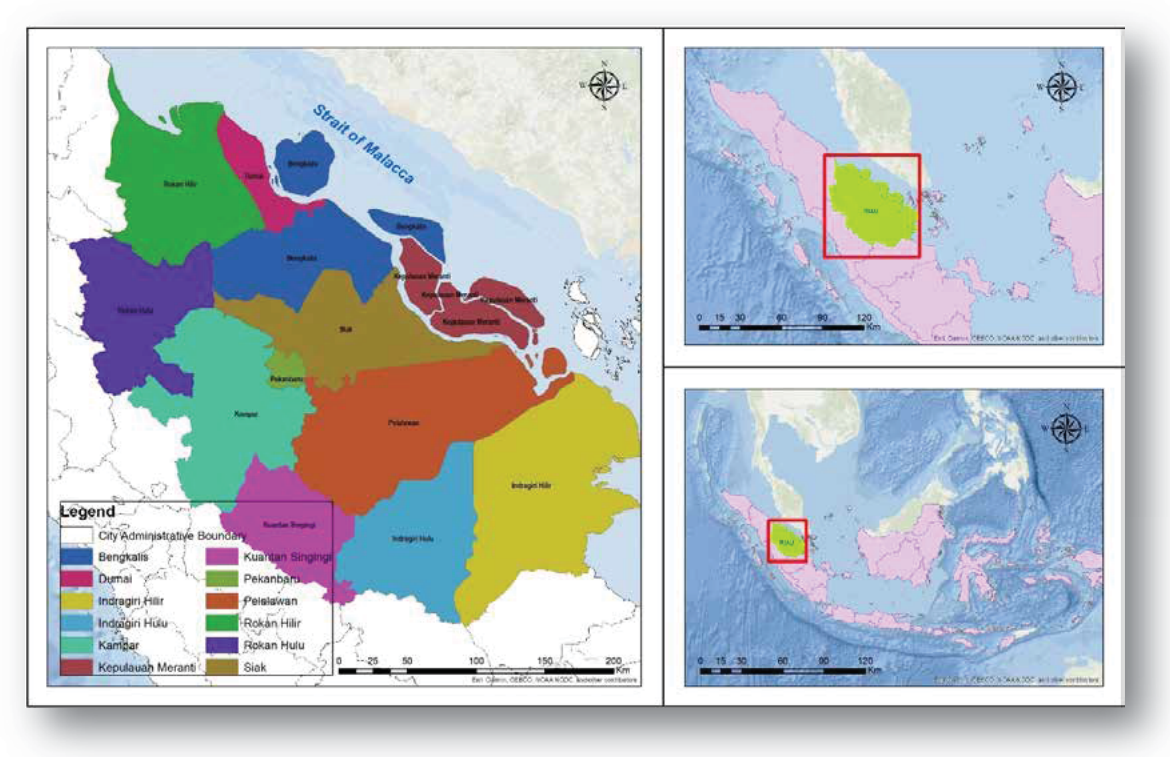


Fig. 1: Georaphic location of the study arae in Riau province, Indonesia

Table 1: Stakeholder of palm oil plantation

Stakeholders	Number of informants	Information
Palm oil plantation owner	2	Oil palm plantation owners who also manage oil palm plantations
Palm oil plantation workers	4	Local communities as workers on oil palm plantations
Cattle breeders	1	Local communities that have cattle farms in oil palm plantation areas

with the utilization of palm oil waste in the realms of medicine, agriculture, energy, handicrafts, and animal husbandry. Data analysis was carried out using descriptive statistics. The secondary data used is oil palm plantation data by smallholder farmers in Riau from 2006 to 2022 to calculate and predict palm oil waste. This data on oil palm plantations managed by smallholder farmers was obtained from BPS Riau Province (BPS, 2022a). To deepen the quantitative findings, interviews were conducted with farmers who manage oil palm plantations. Respondents were selected using snowball sampling. This technique involves incorporating advice from reputable sources with expertise in the area of oil palm management. They were invited to talk about processing palm oil waste on their plantations. Interviews were conducted in oil palm plantation areas so that they could demonstrate their activities directly. The study included seven farmers from Kampar Regency, consisting of owners of oil palm plantations, laborers on oil palm plantations, and cattle breeders (Table 1).

Data analysis

Quantitative data pertaining to the inventory of local community knowledge in the processing of palm oil waste was analyzed by computing the frequency

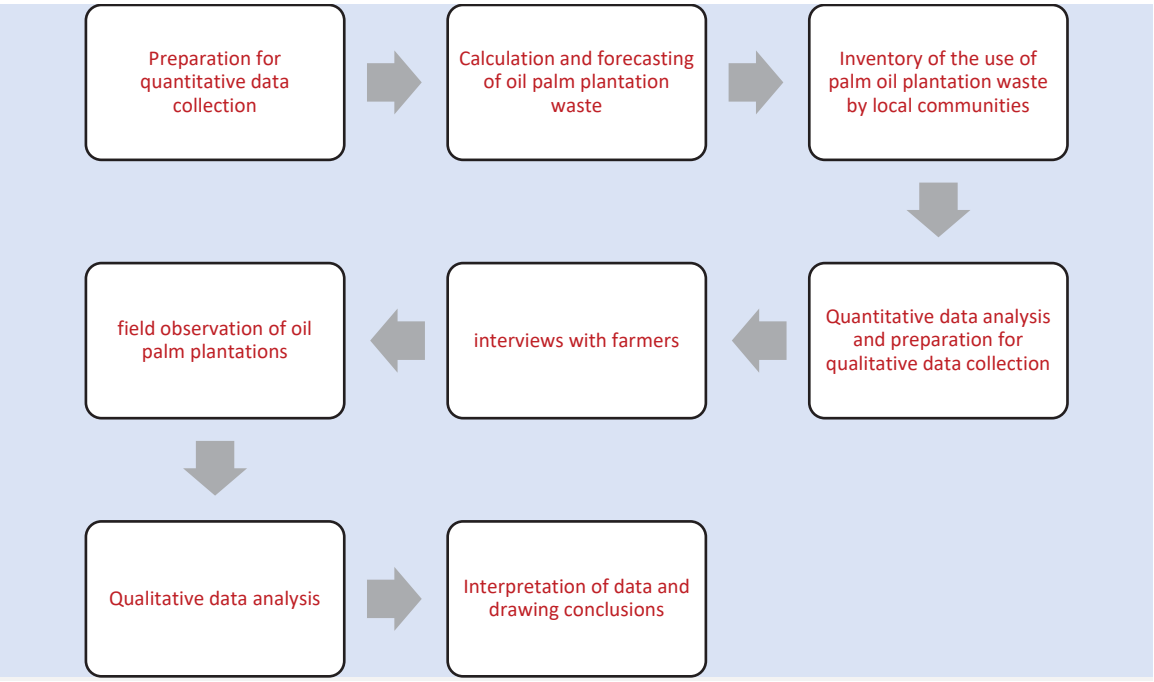


Fig. 2: Flowchart of the study procedure

and percentage of responses provided by participants in the survey. To measure predictions of palm oil waste, researchers used secondary data on oil palm plantations managed by smallholder farmers from 2006-2022 (BPS, 2022a). CPO production data is used to calculate palm oil waste, as presented in Fig. 3. In palm oil processing, 0.24% of CPO is obtained from FFB (BPDPKS, 2022). The calculation results of the palm biomass waste used were plantation waste and FFB processing waste. Plantation residue comprises of leaves and stalks, with quantities determined by the size of the plantation. The frond biomass was calculated at 12 tons/ha per year, and the stem biomass was calculated at 74.5 tons/ha per year (Sung, 2016). FFB waste consists of EFB, shells, and fiber. Calculation of FFB waste biomass is calculated based on CPO production using the mass balance of palm fruit processing, EFB 21%, shells 6.4%, fiber 14.4% (BPDPKS, 2022). The time series modeller method was employed in conducting forecasting analysis, utilizing the Statistical Package for the Social Sciences (SPSS) 23 application, in order to project the quantity of waste expected in the upcoming decade. Data analysis using descriptive statistics and regression. Interview data was analyzed using descriptive-qualitative tools. Data analysis consists of using data reduction, data presentation, and drawing conclusions to provide descriptive answers to research questions (Barrett and Twycross, 2018).

RESULTS AND DISCUSSION

Measurement of palm oil waste from smallholder plantations in Riau province

Palm oil waste consists of plantation waste and FFB waste. Plantation waste consists of fronds and stems. Frond waste is produced every time the fronds are pruned during harvest or maintenance. One or two fronds are usually pruned monthly in old oil palm plantations (Rhebergen *et al.*, 2020), producing a dry weight of 12 tonnes/ha per year. Pruning is an essential task in the upkeep of oil palm trees, aimed at managing their growth effectively. Trimming the fronds of oil palm trees helps minimize potential losses, ultimately leading to enhanced productivity. Stem waste usually occurs during the replanting process. The process of replacing oil palm plants that are no longer productive/economical (>25 years) or have low productivity (<10 tonnes of FFB/ha/year). This process produces stem biomass of 74.5 tons/ha per year. People's oil palm plantations in Riau province

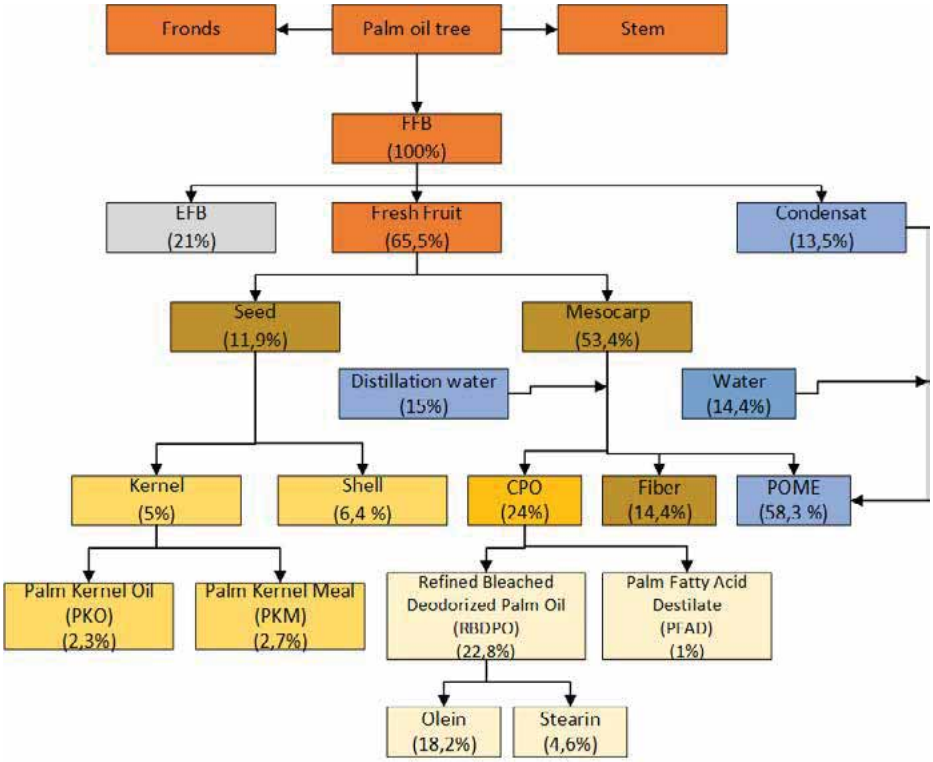


Fig. 3: Mass balance calculation for palm oil processing (BPDPKS, 2022)

continue to expand and have the impact of increasing the waste produced By the year 2022, there will be a total of 1.7 million hectares of smallholder oil palm plantations, yielding a production output of 4.8 million tons. The most enormous waste produced is stems, amounting to 131 million tonnes, and stems, amounting to 21 million tonnes. Meanwhile, FFB waste shows higher EFB than shells and fiber, as seen in Table 2.

EFB waste refers to the byproduct that is left behind following the conversion of FFB from oil palm trees into CPO at palm trees into CPO in palm oil mills. The quantity of FFB waste generated has been steadily increasing year-round. EFB stands out as the most prevalent waste product among the diverse range of FFB wastes, with mesocarp fiber and palm kernel shells following closely behind in terms of abundance. Shell waste generation is the lowest compared to the other two fractions. As illustrated in Fig.4, the most significant increases in palm oil waste production occurred in 2012 and 2018. In 2022, EFB waste reached 4.2 million tons, while shell and fiber waste amounted to 1.2 million tons and 2.8 million tons. The upsurge in palm oil byproducts as a result of the enhanced output of oil palm plantations poses a complicated issue. While high waste production indicates efficient oil extraction, it also necessitates sustainable management practices to mitigate environmental impacts. FFB waste, if not properly utilized, can pollute soil and water bodies. The primary by-product known as empty fruit bunch (EFB) has the potential to decompose and emit methane, a powerful greenhouse gas. Uncontrolled accumulation of EFB can further degrade soil and water quality while also harboring pests and diseases. The study conducted by Asadpour *et al*. (2021) reveals that adapted fiber sourced from EFB can function as a cost-effective absorbent material for addressing oil spills in the marine environment. POME waste is also waste that requires serious handling. Rakhmania *et al*. (2023) show POME can be processed using electrocoagulation to reduce COD, color, and fat effectively. Using platinum as an anode and graphite as a cathode has proven effective

Table 2: Area, CPO Production, FFB, and palm oil waste in smallholder plantations in Riau province 2006-2022

Year	Area (thousands ha)	CPO production (milion Ton)	FFB (million Ton)	EFB (million Ton)	Shells (million Ton)	Fiber (million Ton)	Fronds (million Ton)	Stem (milion Ton)
2006	748	1,779	7,411	1,556	0,474	1,067	8,980	55,753
2007	806	2,055	8,562	1,798	0,548	1,233	9,671	60,043
2008	845	2,368	9,867	2,072	0,631	1,421	10,143	62,970
2009	890	2,658	11,075	2,326	0,709	1,595	10,679	66,299
2010	1.056	2,894	12,060	2,533	0,772	1,737	12,667	78,638
2011	1.205	3,174	13,226	2,777	0,846	1,905	14,466	89,810
2012	1.297	3,485	14,522	3,050	0,929	2,091	15,568	96,648
2013	1.348	3,692	15,384	3,231	0,985	2,215	16,177	100,432
2014	1.358	3,707	15,445	3,244	0,989	2,224	16,294	101,158
2015	1.355	3,612	15,049	3,160	0,963	2,167	16,254	100,910
2016	1.383	3,885	16,186	3,399	1,036	2,331	16,600	103,059
2017	1.529	3,918	16,326	3,429	1,045	2,351	18,348	113,911
2018	1.734	4,789	19,955	4,191	1,277	2,874	20,808	129,180
2019	1.734	4,789	19,955	4,191	1,277	2,874	20,808	129,180
2020	1.762	4,732	19,716	4,140	1,262	2,839	21,146	131,281
2021	1.762	4,818	20,074	4,216	1,285	2,891	21,146	131,281
2022	1.762	4,818	20,076	4,216	1,285	2,891	21,146	131,281

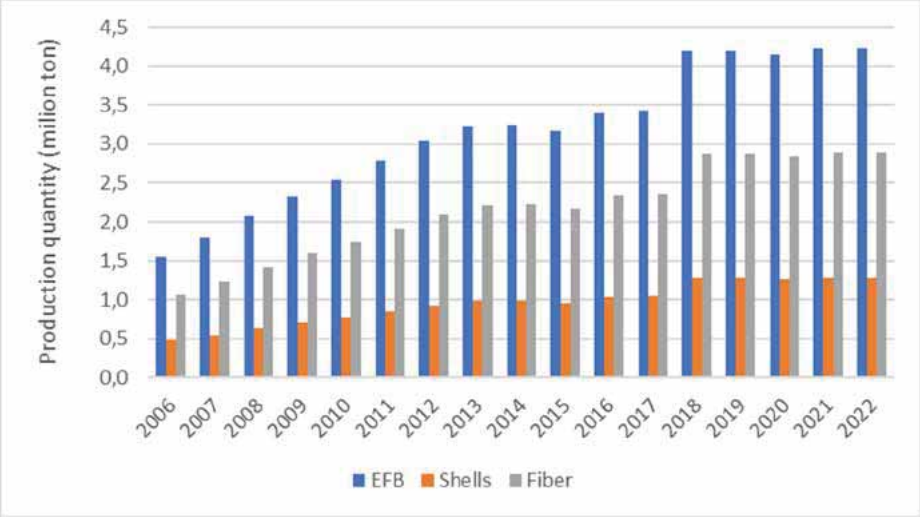


Fig. 4: Palm oil fresh fruit bunch waste in people's plantations in Riau province

in the electrochemical oxidation process of POME (Rakhmania *et al*., 2022). Jadhav *et al*. (2024) show POME can act as a medium for making biogas. Palm fruit fibers, a residual product of palm oil extraction, may also present possible environmental hazards. It is crucial to prioritize sustainable management strategies for palm oil waste in order to minimize adverse environmental effects. Prioritizing sustainable management strategies for palm oil waste is critical to mitigate negative environmental impacts. EFB waste holds the potential to be transformed into a valuable environmental resource. The elevated level of organic matter present enables the conversion into premium-grade compost. Utilizing such compost can enhance soil fertility, thereby reducing reliance on chemical fertilizers. EFB can be converted into biogas, a clean and renewable energy source.

Oil palm plantations produce substantial amounts of biomass waste, with fronds and stems comprising the largest portion of this waste. This waste production

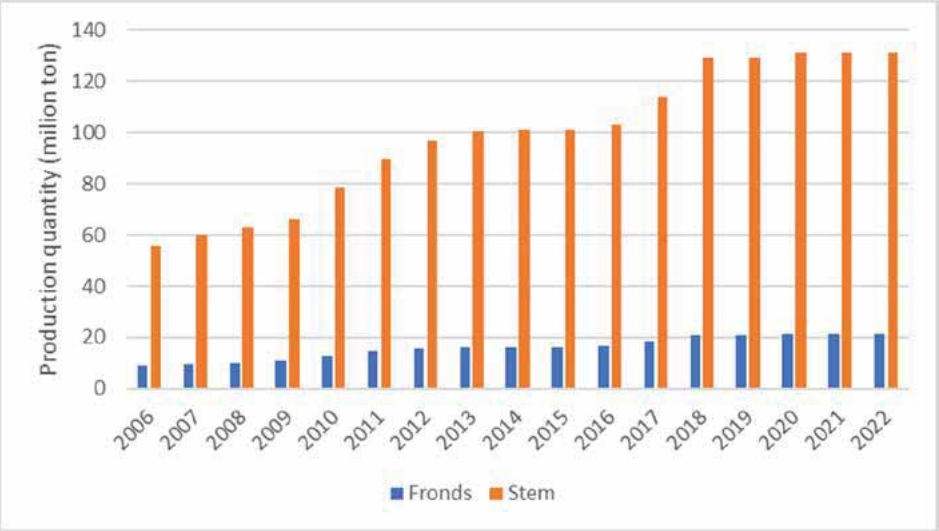


Fig. 5: Palm oil frond and stem waste in people's plantations in Riau province

exhibits a continuous upward trend throughout the year, with fronds exceeding stem waste in quantity. It is important to highlight that these two waste streams exceed EFB, shells, and fibers in terms of total waste generation. The observed rise in waste production coincides with substantial expansion of plantation areas, particularly in 2012 and 2018. As of 2022, projections indicate stem waste reaching 131.2 million tonnes, while frond waste is expected to reach 21.1 million tonnes (Fig. 5).

An oil palm frond comprises roughly 100 leaves, each possessing a lamina, midrib, petiole, and petiole base. The length of these leaves usually falls within the range of 55 to 65 centimeters (cm), while their width narrows down to 2-4 cm in width. Mature fronds can reach up to 7.5 cm in width, with a leaf stalk measuring approximately one-quarter of the total frond length. Frond length can vary between 5-9 meter (m). (Hambali and Rivai, 2017). This frond has a high-fiber lignocellulosic material consisting of cellulose (31,5%) and hemicellulose (19,2%) (Ooi *et al*., 2017) and representing 65% of the total fiber content (Ikubar *et al*., 2018). Frond biomass, a crucial secondary product of the oil palm sector, originates from two main sources: the replanting of mature oil palm trees (aged 25-30 years) and regular pruning procedures. Oil palm plantations can be categorized into three stages: mature, immature, and non-mature. This study indicated that there will be a sustained growth in the establishment of oil palm plantations over the next 15 years. Government policies play a crucial role in managing this expansion. Regional regulations, exemplified by Riau Province's Provincial Spatial Planning (RTRWP) outlined in Regional Regulation No. 10 of 2018, set limitations on the total plantation area (restricted to 3.1 million ha in this case). Presidential Instruction No. 8 of 2018 pertains to the postponement of palm oil plantation licensing evaluations. Addressing the issue of palm oil waste necessitates a comprehensive strategy that goes beyond mere policy interventions. Enhancing the caliber of human capital is of equal significance. The education sector can significantly contribute by fostering awareness of sustainable palm oil practices within the younger generation. The educational emphasis aims to prepare upcoming decision-makers with the necessary knowledge and abilities to manage the intricate equilibrium between the expansion of the palm oil industry growth and environmental sustainability.

Forecasting palm oil waste from smallholder plantations in Riau Province 2023-2035

Production projections for EFB, shells, fibers, palm fronds, and palm stems from smallholder plantations were calculated using data spanning 2006 to 2022 (Table 3). The study utilized a time series modeling technique to predict the amount of waste generated, aiming to assess the future potential of palm oil waste production in Riau Province for the upcoming decade.

Table 3: Forecasting of palm oil waste in smallholder plantations in Riau province 2023-2035

Year	EFB (million Ton)	Shells (million Ton)	Fiber (million Ton)	Fronds (million Ton)	Stem (milion Ton)
2023	4,382	1,336	3,005	21,906	136,002
2024	4,548	1,386	3,119	22,667	140,722
2025	4,715	1,437	3,233	23,427	145,443
2026	4,881	1,488	3,347	24,187	150,163
2027	5,047	1,538	3,461	24,948	154,884
2028	5,213	1,589	3,575	25,708	159,604
2029	5,380	1,639	3,689	26,468	164,325
2030	5,546	1,690	3,803	27,229	169,045
2031	5,712	1,741	3,917	27,989	173,766
2032	5,878	1,791	4,031	28,749	178,486
2033	6,044	1,842	4,145	29,510	183,207
2034	6,211	1,893	4,259	30,270	187,927
2035	6,377	1,943	4,373	31,030	192,647

This approach enables estimation of the anticipated waste quantities in the coming years. The resulting projections will illuminate the potential scale of palm oil waste production in Riau Province by 2035.

Projections indicate a notable increase in the generation of palm oil waste in the upcoming years. It is anticipated that by the year 2035, the production of stem and frond waste will escalate to 192 million tonnes and 31 million tonnes, respectively.FFB waste, categorized as EFB, shells, and fibers, is projected to reach 6.3 million tonnes, 1.9 million tonnes, and 4.3 million tonnes. This upward trend contrasts with the 2030 target year for achieving the sustainable development goals (SDGs). In 2030, the reported production of EFB waste, shells, fibers, palm fronds, and palm stems was 5.5 million tonnes, 1.6 million tonnes, 3.8 million tonnes, 27.2 million tonnes, and 169 million tonnes. The data presented underscores a pressing issue for individuals invested in the palm oil sector. Effectively handling the increasing amount of palm oil byproducts is crucial for maintaining an environmentally sustainable framework. The concerning forecast of rising palm waste is further illustrated in Figs. 6 and 7.

The establishment of plantations, particularly those of oil palm, demonstrates a significant level of public interest in this particular crop. The cultivation of oil palms has resulted in improved living standards for rural populations engaged in various aspects of the oil palm agribusiness (Hariyanti *et al*., 2024). Palm oil has been a superior commodity for both the community and agribusiness companies. For the community, especially farmers, oil palm is a coveted crop and a source of family income that leads to prosperity. The rural economy has experienced a significant increase as a result of the expansion of palm oil agribusiness.

Inventory of local community knowledge in palm oil waste processing

A compilation of their expertise was created in order to evaluate the local community's comprehension of waste utilization methods. This study collected information on demographics as well as knowledge-based data. The demographic data encompassed variables such as sex, age, marital status, educational attainment, employment status, and geographical background. Knowledge-based data focused on specific areas of waste application, encompassing medicine, agriculture, energy production, handicrafts, and animal husbandry. As shown in Table 4, a total of 112 individuals participated in the survey. The survey indicated a significant level of consciousness among the residents of Riau concerning the existence of oil palm plantations. Table 4 further details the regional distribution of respondents across various regencies within Riau province. The Meranti Islands

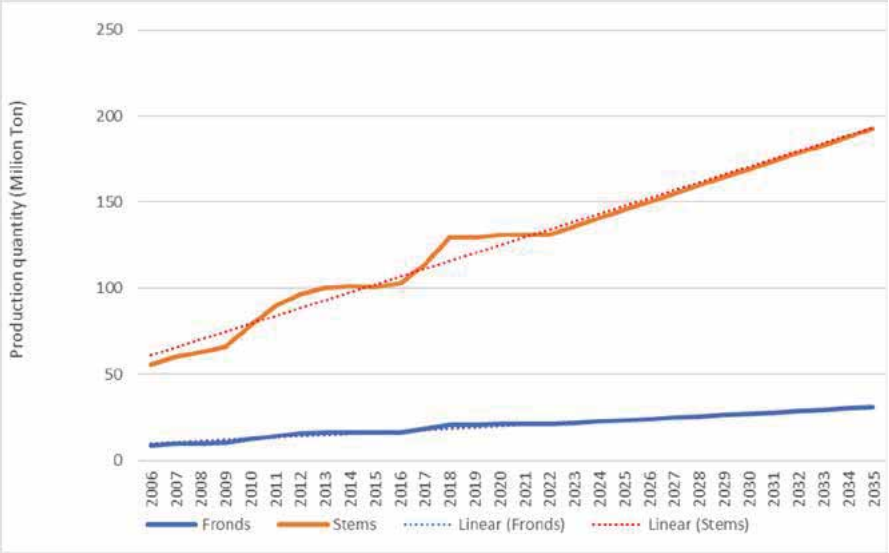


Fig. 6: Trend of fronds and stems waste from palm oil plantations 2006-2035

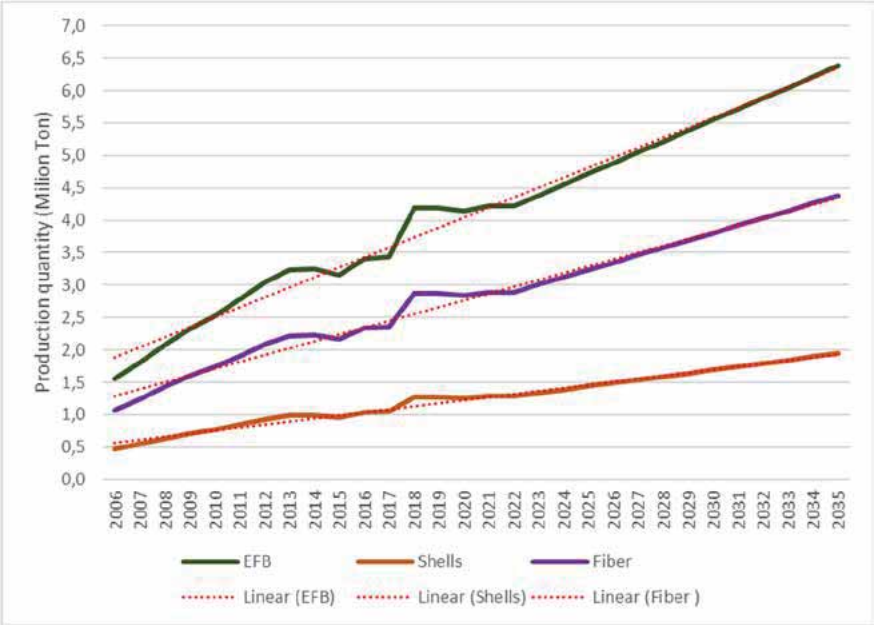


Fig. 7: Trends in EFB, Shell, and Fiber Waste 2006-2035

district stands out as the sole region lacking oil palm plantations. The lack of presence in this area can be explained by a mix of environmental and infrastructural constraints, as well as the choice of the local government to withhold permits for the expansion of palm oil production. Community members have voiced worries about the sinking of land, a possible outcome that may jeopardize the sustainability of the area given its close proximity to sea level.

The local community has utilized a portion of plantation waste products. Organic fertilizer,

Table 4: Knowledge of palm oil waste management by the people of Riau

Aspect	Indicator	frequency	Percentage
	Demographic data		
Gender	Male	23	21%
	Female	88	79%
Age	15 - 18 years	7	6%
	19 - 24 years	90	81%
	> 25 years	14	13%
Marital status	Married	14	13%
	Unmarried	97	87%
Education level	Doctoral degree	1	1%
	Master's degree	6	5%
	Bachelor's degree	33	30%
	High School	71	64%
Occupation	Local community	84	76%
	Farmer	27	24%
Place/Regency	Bengkalis	5	5%
	Indragiri Hilir	6	5%
	Indragiri Hulu	5	5%
	Kampar	13	12%
	Kuantan Singingi	8	7%
	Pelalawan	16	14%
	Rokan Hilir	12	11%
	Rokan Hulu	12	11%
	Siak	7	6%
	Dumai	4	4%
	Pekanbaru	23	21%
	Knowledge		
Medicine	Wound healer	10	9%
	Hypertension	1	1%
	Muscle pain	2	2%
	Stomachache	1	1%
	Anti-inflammatory	1	1%
Agriculture	Organic fertilizer	87	78%
	Mushroom growing medium	40	36%
Energy	Firewood	64	58%
	Briquette	21	19%
Handicraft	Broom	29	26%
	Roof	8	7%
	Woven plate	13	12%
	Woven basket	2	2%
	Mat	3	3%
	Hat	3	3%
	Bag	3	3%
Animal husbandry	Animal pen construction	11	10%
	Livestock feed	44	40%

employed by 78% of the community, and mushroom cultivation medium (36%) are the primary applications for this waste. EFB, palm fronds, and seashells have the potential to be decomposed into organic fertilizer, leading to improved soil quality and increased agricultural productivity. The manufacturing procedure is simple and economical. EFB Waste or palm shells are composted through

microbial breakdown. A substantial portion of the community relies on natural decomposition without additional interventions. Local communities directly utilize palm waste, mainly leaves, for composting purposes. The palm fronds that have been pruned from the trees are carefully positioned among the palm trunks, as depicted in Fig. 8. Some farmers create a circular arrangement around each palm tree to optimize nutrient absorption. This method is rooted in the belief that the breakdown of leaves adds crucial nutrients to support the growth of palm oil.

Oil palm cultivation necessitates regular pruning of fronds to maintain tree health and productivity. he fronds are commonly collected in a circular heap around the trunk for the purpose of composting. Despite seeming simple at first, certain farmers opt to position the pruned fronds directly among the palm trees. This practice allows palm roots to grow beneath the accumulating frond layer. it's crucial to note that palm fronds are non-productive biomass requiring regular removal to ensure tree health. The decomposition of palm fronds is a complex procedure that encompasses a variety of microbial populations. The initial decomposition phase involves primary decomposers like bacteria and fungi, which break down readily available organic components like sugars and amino acids. These microorganisms tackle more complex organic matter such as cellulose, hemicellulose, and lignin (Uke *et al*., 2021). The process of composting effectively boosts soil fertility through the augmentation of organic matter levels, consequently stimulating the development of oil palm and various other crops (Azman *et al*., 2023). Palmoil waste holds potential in the medical sector, particularly for wound healing, muscle pain relief, and reducing inflammation. Wound healing is the most prevalent application. People have used traditionaly palm fronds and palm oil itself to treat wounds. The findings from the study conducted by Rajoo *et al*. (2021) indicated that palm oil has the potential to enhance the proliferation of fibroblasts, which play a vital role in the healing process of burn injuries. This effect is attributed to the presence of flavonoids, particularly flavonoid C-glycosides, within palm oil. demonstrate therapeutic advantages by functioning as antioxidants and facilitating the process of wound healing. Tow *et al*., (2021) in their research showed that similar properties are found in palm leaves, which are rich in these same flavonoid



Fig. 8: Use of palm fronds as compost a) arranging palm fronds in a circle b) arranging palm fronds between trees c) new roots growing under a pile of palm fronds

C-glycosidesPalm leaves possess antioxidant and anti-inflammatory properties, which make them promising candidates for wound-healing agents (Zain *et al*., 2020). These leaves contain alkaloids, tannins, and saponins, all with established antimicrobial properties, which aid in combating bacteria and other microorganisms that can impede wound healing. People awareness regarding the utilization of palm oil waste for energy generation is still lacking. A study revealed that most individuals (58%) are acquainted with the practice of using palm oil waste as firewood, whereas only 19% are aware of its potential for producin briquettes. This highlights a gap in public knowledge concerning more sustainable and efficient energy utilization from palm oil waste. The research results of Bazargan *et al*. (2018) demonstrated that briquettes produced from palm oil shell waste meet high-quality standards. The briquettes present notable benefits in comparison to conventional fossil fuels. EFB can also be utilized as a raw material for briquettes due to its high carbon content (44.9%) (Farid *et al*., 2020). Research results Amrullah *et al*. (2020) showed that EFB briquettes boast the highest heating value among various options, reaching 5,475 cal/g. The high carbon content in EFB (46.62%) further reinforces its suitability for bio-briquette production. The briquettes are not just eco-friendly, producing reduced levels of greenhouse gas emissions, but they are also economical and easily accessible (Musabbikhah *et al*., 2015). The utilization of palm oil waste for the production of briquettes offers fresh prospects for economic growth within communities, with the potential to bolster income levels and foster job creation. To bridge the knowledge gap, educational initiatives are crucial to raise public awareness regarding the potential of palm oil waste briquettes as a sustainable and beneficial energy source. Palm oil byproducts are utilized in the creation of handicrafts, with a particular focus on leaves, fronds, and sticks. The processed house products include brooms (26%), roofs (7%), plates (12%), baskets (2%), mats (3%), hats (3%) and bags (3%). The majority of people make brooms from palm tree sticks. Using palm oil waste as raw material for handicrafts shows people's creativity and concern for the environment. Previously considered waste products, palm leaves, fronds, and stalks can be upcycled into a diverse range of unique and valuable handicraft goods. The transition to using these resources offers a substantial chance for economic growth. The resulting handicrafts, often employing stick-weaving techniques, hold potential for both domestic and international markets. Oil Palm tree components, from delicate fronds to sturdy stalks, can be transformed into a variety of functional and decorative items, including household furniture and home decor accents. The accessibility of these raw materials helps to reduce production expenses due to their low initial investment requirements. The selling price of stick crafts such as hats, hats, and bags has a high selling value (Abdullah *et al*., 2020). Craft training for palm oil farmers is an important step to improve their economy and welfare. Fitria *et al*. (2021) showed that training for local communities can increase their creativity in utilizing palm oil waste. The creative products produced can increase people's income (Kemala *et al*., 2023). In addition to their economic significance, handicrafts made from palm oil waste also possess ecological value. Utilizing this waste contributes to reducing environmental pollution and minimizing the accumulation of waste in palm oil plantations. In the livestock sector, local communities use plantation waste to make pens (10%) and animal feed (40%). Livestock enclosures are constructed by the community utilizing resources sourced from palm stems and palm fronds. Durable and resilient palm oil stems are transformed into the necessary raw materials. The main thing for making cages is that the broad and waterproof palm fronds are used as roofs. The stem's lignin content varies between 6.213% and 33.702%, showing an increase in lignin value from the base middle section to a decrease towards the tip. The palm oil waste processing process carried out by the community can contribute to reducing environmental pollution and minimizing the accumulation of waste in palm oil plantations. Aligned with research by Sumiyati *et al*. (2024), effective and efficient agricultural waste management can contribute to climate change mitigation and the establishment of a circular economy. Apart from that, palm oil waste processing can contribute to reducing environmental pollution and minimizing the accumulation of waste in palm oil plantations. Palm oil plantations are further utilized in the production of animal feed that is abundant in essential nutrients. Palm leaves, bunch skin, and palm kernel cake can be fermented or processed using other processes to produce cheap, high-quality animal feed. Palm oil

cake can serve as a valuable feed option for cattle (Grinnell *et al*., 2022). Integrating oil palm plantations and cattle farming is a viable strategy for small farmers to increase resource use efficiency on plantations (Tohiran *et al*., 2019) and beef self-sufficiency (Grinnell *et al*., 2022). Cattle farmers use palm oil waste, known as solid. Local people often call it *blondho* palm. Solid palm oil has a soft texture like tofu dregs, is dark brown, and has a sweet and sour smell. It contains 1.5% CPO oil, so in the open air, it quickly becomes rancid, and if left for 2-3 days, mold will appear. The fungi were recognized as *Monilia sp*. and *Candida sp*. and pose no threat. (Saelor *et al*., 2024). The product finds application in reducing reliance on traditional grass feed while simultaneously promoting increased cattle weight gain. It can be offered to cattle in either their fresh form or a compressed block format, known as "solid bread". The incorporation of palm solids into the diet of cattle provides farmers with a flexible feeding option through this approach. This "solid bread" contains solid palm oil and other basic ingredients such as palm kernel meal, molasses, salt, minerals, and protein content. It is made in two forms: fermented and unfermented. The fermenter used is tempeh yeast or effective microorganisms (EM-4), which is widely sold The tempeh yeast is applied to fresh solids, which are subsequently enclosed and left to ferment for a period of seven days. Following the fermentation process, the end product exhibits a unique scent and is adorned with mycelium. The fermented solid product contains the fungi *Aspergillus niger*, *Aspergillus oryzae* and *Aspergillus lumori*. The fermentation process by these fungi has the highest level of non-fiber carbohydrates, 20.3% and 13.94%, which increases the product's nutritional value (Oliveira et al., 2018). The use of solid palm oil for animal feed can increase body weight because it improves nutritional quality and rumen digestibility in vitro (Rofiq et al., 2021). Using this bread can reduce feed costs and does not cause negative effects. Solid palm oil has great potential as a source of animal feed. The significance of this study lies in its contribution to advancing the development of sustainable palm oil plantations in Riau Province. Oil palm plantations have become deeply ingrained in the regional identity. Riau boasts the highest CPO production nationwide, contributing substantially to the Indonesian economy. Findings highligh the high volume of palm oil waste and inadequate waste management practices employed by small-scale farmers raise concerns. The continuous growth of these agricultural estates requires particular attention from governmental regulatory agencies. Socialization of regulations established by the Roundtable on Sustainable Palm Oil (RSPO) and Indonesian Sustainable Palm Oil (ISPO) initiatives is crucial for promoting environmentally responsible practices in palm oil production. The limitation of this study is that it only takes an inventory of the use of palm oil waste in Riau Province, so it could be utilized more if explored in other areas. This study delves into the waste accounting and management strategies employed in local communities, presenting factual discoveries and implications that could guide influential policy proposals. Land-use planning policies should prioritize a balanced approach, considering the correlation between plantation area and waste management. Policymakers must prioritize land management strategies that prioritize both economic development and long-term environmental sustainability. The anticipated expansion of oil palm plantations underscores the critical need for robust waste management infrastructure within the region. The commendable actions taken by the government to enhance the capabilities of RSPO and ISPO certification bodies contribute to the promotion of effective and responsible palm oil management practices. Effective policy measures include the implementation of sustainable agricultural practices coupled with appropriate incentives for landowners, particularly during replanting cycles. Adhering to established regulations by implementing suitable replanting stages can significantly decrease land utilization. This aligns with the findings of Siregar *et al* (2024), whose research indicates that uncontrolled plantation expansion can exacerbate deforestation rates. Enhancing farmers' skills in waste management presents an opportunity to unlock economic value. The strategy can be achieved by means of actions like enhancing farmer cooperatives, offering support for infrastructure development, easing the process of obtaining funding, and promoting the marketing of goods resulting from waste management techniques. Community involvement and education initiatives play a critical role in environmental improvement efforts. Engaging local communities and providing them with educational programs fosters awareness

regarding the importance of environmental protection. Policy frameworks must place a strong emphasis on community involvement as a fundamental element in fostering the growth of sustainable palm oil plantations. The incorporation of these policy suggestions into comprehensive environmental management plans enables policymakers to protect ecosystems, advance sustainable development, and foster a green economy within Riau Province.

CONCLUSION

The results presented in this study provide crucial information for formulating strategies in waste management aimed at promoting the long-term viability of small-scale oil palm farms. This approach has facilitated a detailed understanding of the waste profile and the extent of use by local communities, thus proving invaluable for ecological studies and the basis of policies for realizing sustainable palm oil plantations. The proliferation of plantations results in a notable rise in the amount of waste generated. Smallholder palm oil plantations will contribute around 121,2 million tons of waste, consisting of 3.1 million tons of EFB, 1 million tons of shells, 2.2 million tons of fiber, 15.9 million tons of fronds, and 98.9 million tons of stems. The rise in global demand for palm oil has led to the expansion and intensification of palm oil plantations worldwide. The prediction results are that the area of oil palm plantations in the next ten years will increase significantly and is directly proportional to the increase in waste production. Based on forecasting methods, the amount of palm oil waste in the next decade will be 236.37 million tons, consisting of 6.37 million tons of EFB, 1.94 million tons of shells, 4.3 million tons of fiber, 31 million tons of fronds and 192.26 million tons of stems. Palm oil waste has been utilized by local communities for medicinal purposes, agricultural activities, energy production, crafting, and animal husbandry. People can use palm oil waste leaves in medicine for wound healing, muscle pain, and anti-inflammation. The majority of people use it more as a wound healer. Most people use the stems as compost by letting the remaining pruning products decompose naturally on plantations. People also use more plantation waste, especially fronds, as firewood. Nevertheless, certain individuals utilize fronds, foliage, and twigs as crafting supplies for the production of domestic tools like dishes, brooms, purses, containers, and rugs. The community uses palm oil waste from CPO processing residues as cattle feed. This combined approach not only determines the amount of waste quantitatively but also obtains findings from the community regarding the management of their plantation waste. The results presented in this study provide crucial information for formulating strategies in waste management aimed at promoting the long-term viability of small-scale oil palm farms. Waste management in small oil palm plantations in Riau shows that it is still low. Policymakers (government) should use these findings. This study offers an insightful analysis on the capacity of palm oil waste to promote the proper handling of palm oil plantation byproducts in order to mitigate environmental contamination. The main challenge in managing palm oil plantation waste in Indonesia is the limited understanding of local farmers about the diversification of palm oil waste use and its potential for strengthening the economy. It is recommended that training initiatives be provided to local communities in order to enhance their abilities and capabilities in carrying out waste management procedures for palm oil plantations. The participation of scholars plays a crucial role in spreading evidence-based information and enhancing community capabilities in handling waste from palm oil plantations. Integrating the traditional ecological knowledge of local communities is also very important in planning and implementing waste management. Establishing farmer associations in partnership with diverse stakeholders has the potential to enhance the economic viability of the community and promote the enhancement of the ecosystem.

AUTHOR CONTRIBUTIONS

T. Hidayat, the corresponding author, contributed to conceptualizing the research idea and instructed other authors to analyze and summarize the research results, including advice on techniques, methods, and manuscript writing. Riandi has participated in the interpretation of the results and the review of the manuscript. A. Ilhami collected, analyzed data and wrote a manuscript.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to (1) the Ministry of Education, Culture, and Technology (KEMDIKBUDRISTEK) grant number [082/

E5/PG.02.00.PL/2024] and grant number [1226 / UN40.LP/PT.01.03/2024] Institute for Research and Community Service [LPPM] Universitas Pendidikan Indonesia, and (2) *Lembaga Pengelola Dana Pendidikan* (Indonesia Endowment Fund for Education)-LPDP, Ministry of Finance Indonesia for granting a scholarship BIB (*Beasiswa Indonesia bangkit*) and supporting the publication of this article.

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

©2024 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 ille or format, as long as you give appropriate credit to the original ill(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 illes the permitted use, you ill 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
BPDPKS	*Badan Pengelola Dana Perkebunan Kelapa sawit* (Palm oil plantation fund management agency)
BPS	*Badan Pusat Statistik* (Central statistics agency)
cal	Calories
cm	Centimeter
CPO	Crude Palm oil
EF	Effective microorganisms
EFB	Empty fruit bunches
FFB	Fresh fruit bunch
g	Gram
ha	Hectare
Inpres	*Instruksi presiden* (Presidential decree)
ISPO	*Indonesian Sustainable Palm Oil*
m	Meter
mm	Milimeter
PFAD	Palm fatty acid destilate
PKO	Palm kernel oil
PKM	Palm kernel meal
POME	Palm oil mill effluent
RBDPO	Refined bleached deodorized palm oil
RSPO	Roundtable on Sustainable Palm Oil practices
RTRWP	*Rencana Tata Ruang Wilayah Provinsi* (Provincial spatial plan)
s	Second
SDGs	*Sustainable development goals*

REFERENCES

Abdullah; Khan, S.M.; Pieroni, A., Haq, Z.U.; Ahmad, Z. (2020). Mazri (Nannorrhops ritchiana (Griff) Aitch.): A remarkable source of manufacturing traditional handicrafts, goods and utensils in Pakistan. J. Ethnobiol. Ethnomed., 16(1): 1–13 **(13 pages)**.

Ahmed, A.; Mohd, Y.B.I.; Abdullah, A.M., (2021). Oil palm in the face of climate change: A review of recommendations. IOP Conference Series: Earth Environ. Sci., 646(1): 1-10 **(10 pages).**

Asadpour, R.; Yavari, S.; Kamyab, H.; Ashokkumar, V.; Chelliapan, S.; Yuzir, A., (2021). Study of oil sorption behaviour of esterified oil palm empty fruit bunch (OPEFB) fibre and its kinetics and isotherm studies. Environ. Technol. Innovation., 22: 1-12 **(13 pages).**

Amrullah, M.; Mardawati, E.; Kastaman, R.; Suryaningsih, S., (2020). Study of bio-briquette formulation from mixture palm oil empty fruit bunches and palm oil shells. IOP Conference Series: Earth Environ. Sci., 443(1): 1-6 **(6 pages).**

Ayompe, L.M.; Schaafsma, M.; Egoh, B.N., (2021). Towards sustainable palm oil production: The positive and negative impacts on ecosystem services and human wellbeing. J. Cleaner Prod., 278: 1-11 **(11 pages).**

Azman, N.F.; Katahira, T., Nakanishi, Y., Chisyaki, N., Uemura, S., Yamada, M., Takayama, K., Oshima, I., Yamaguchi, T., Hara, H.; Yamauchi, M., (2023). Sustainable oil palm biomass waste utilization in Southeast Asia: Cascade recycling for mushroom growing, animal feedstock production, and composting animal

excrement as fertilizer. Cleaner Circ. Bioecon., 6(9):1-9 **(8 pages).**
Barrett, D.; Twycross, A., (2018). Data collection in qualitative research. Evidence-Based Nursing. 21(3): 63–64 **(2 pages).**
Bazargan, A.; Rough, S.L.; McKay, G., (2018). Fine tuning of process parameters for improving briquette production from palm kernel shell gasification waste. Environ. Technol., 39(7): 931–938 **(8 pages).**
BPDPKS, (2022). Neraca Massa pengolahan Sawit. Palm Oil Plantation Fund Management Agency, Jakarta.
BPS, (2022a). Statistik Indonesia 2022. In Statistik Indonesia (Vol. 1101001). Central Bureau of Statistics, Jakarta.
BPS, (2022b). Statistik Kelapa Sawit Provinsi Riau. Vol. 3. Central Bureau of Statistics, Riau.
Cifuentes-Espinosa J.A.; Feintrenie, L.; Monzón-AlvaradoC.; Schmook, B.; Mesa-Jurado M.A., (2023). Oil palm growers' prospects for sustainable oil palm production. A case study from Campeche, Mexico. Agric. Syst., 212: 1-17 (**17 pages).**
Creswell, J.; Guetterman, T., (2019). Educational research. Pearson Education, New York.
Farid, M.A.A.; Hassan, M.A.; Roslan, A.M.; Samsudin, M.H.; Mohamad, Z.J.J.; Othman, M.R.; Shirai, Y., (2020). Carbon monoxide reduction in the flue gas during biochar production from oil palm empty fruit bunch. J. Cleaner Product., 258: 1–9 **(9 pages).**
Fitria, D.; Putra, I.U.; Tambunan, D.R.; Susanti, M., (2021). Training the utilization of palm oil waste supporting village community economy. Int. J. Sci. Technol. Manage., 2(4): 1234–1248 **(15 pages).**
Grinnell, N.A.; Linden, A.V.D.; Azhar, B.; Nobilly, F.; Slingerland, M., (2022). Cattle-oil palm integration – a viable strategy to increase Malaysian beef self-sufficiency and palm oil sustainability. Livestock Sci., 259: 1-14 **(14 pages).**
Hambali, E.; Rivai, M., (2017). The potential of palm oil waste biomass in Indonesia in 2020 and 2030. IOP Conference Series: Earth Environ. Sci., 65(1): 1-9 **(9 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): 1-17 **(17 pages).**
Hassan, M.A.; Farid, M.A.A.; Zakaria, M.R.; Ariffin, H.; Andou, Y.; Shirai, Y., (2024). Palm oil expansion in Malaysia and its countermeasures through policy window and biorefinery approach. Environ. Sci. Policy. 153,1-19 **(19 pages).**
Ikubar, M.R.M.; Manan, M.A.; Salleh, M.; Yahya, A., (2018). Solid-state fermentation of oil palm frond petiole for lignin peroxidase and xylanase-rich cocktail production. 3 Biotech., 8(5): 1-11 **(11 pages).**
Indrajaya, Y.; Yuwati, T.W.; Lestari, S.; Winarno, B.; Narendra, B.H.; Nugroho, H.Y.S.H.; Rachmanadi, D.; Pratiwi; Turjaman, M.; Adi, R.N., (2022). Tropical forest landscape restoration in Indonesia: A review. Land. 11(3): 1-37 **(37 pages).**
Jadhav, P.; Krishnan, S.; Kamyab, H.; Khalid, Z.B.; Bhuyar, P.; Zularism, A.W.; Nasrullah, M., (2024). Characterisation of synthesised trimetallic nanoparticles and its influence on anaerobic digestion of palm oil mill effluent. Chemosphere. 346: 1-9 **(10 pages).**
Kemala, Z.; Hasanah, P.H.; Tanti, G.E.; Damanik, N.P.; Wiratama, W., (2023). Analysis of the use of palm oil slipping in increasing Talun Kondot II village communities income. Asian J. Eng. Soc. Health. 2(2): 127–135 **(8 pages).**
Lai, J. W.; Ramli, H.R.; Ismail, L.I.; Hasan, W.Z., (2023). Oil palm fresh fruit bunch ripeness detection methods: A systematic review. Agriculture. 13(1): 1-16 **(16 pages).**
Manurung, G.M.E.; Siregar, Y.I.; Syahza, A.; Suwondo, S., (2021). Opportunity for sustainable palm oil practices by smallholder farmers in Riau. J. Hunan Univ. Nat. Sci., 48(10): 28–35 **(8 pages).**
Murphy, D.J.; Goggin, K.; Paterson, R.R.M., (2021). Oil palm in the 2020s and beyond: challenges and solutions. CABI Agric. Biosci., 2: 1–22 **(22 pages).**
Musabbikhah, M.; Saptoadi, H.; Subarmono, S.; Wibisono, M.A., (2015). Optimization of biomass briquettes production process using taguchi method. J. Manusia dan Lingkungan. 22(1): 121–128 **(8 pages).**
Nasution, Z.P.S.; Amalia, R.; Nurkhoiry, R.; Oktarina, S.D.; Nasution, M.A., (2021). Assessing the appropriate technology options on utilizing oil palm biomass for rural development in Riau Province. Proc. 1st Int. Conf. Sustain. Agric. Socio-Econ Agribusiness, Rural. Dev., 199: 70–75 **(6 pages).**
Oliveira, A.C.; Amorim, G.M.; Azevêdo, J.A.G.; Godoy, M.G.; Freire, D.M.G., (2018). Solid-state fermentation of co-products from palm oil processing: Production of lipase and xylanase and effects on chemical composition. Biocatal. Biotransform. 36(5): 381–388 **(8 pages).**
Ooi, Z.X.; Teoh, Y.P.; Kunasundari, B.; Shuit, S.H., (2017). Oil palm frond as a sustainable and promising biomass source in Malaysia: A review. Environ. Progress Sustainable Energy. 33(3): 1-11 **(11 pages).**
Petrenko, C.; Paltseva, J.; Searle, S., (2016). Ecological impacts of palm oil expansion in Indonesia. Int. Council Clean Transport. Washington: 1–21 **(21 pages).**
Pulingam, T.; Lakshmanan, M.; Chuah, J.A., Surendran A.; Zainab-L, I.; Foroozandeh, P.; Uke, A.; Kosugi, A.; Sudesh, K., (2022). Oil palm trunk waste: Environmental impacts and management strategies. Ind. Crops Products. 189(2): 1-14 **(14 pages).**
Raharja, S.; Marimin; Machfud; Papilo, P.; Safriyana; Massijaya, M.Y.; Asrol, M.; Darmawan, M.A., (2020). Institutional strengthening model of oil palm independent smallholder in Riau and Jambi Provinces, Indonesia. Heliyon. 6(5): 1-17 **(17 pages).**
Rajoo, A.; Ramanathan, S.; Mansor, S.M.; Sasidharan, S., (2021). Formulation and evaluation of wound healing activity of Elaeis guineensis Jacq leaves in a Staphylococcus aureus infected Sprague Dawley rat model. J. Ethnopharmacol., 266: 1- 9 **(9 pages).**
Rakhmania,; Kamyab, H.; Yuzir, M.A.; Al-Qaim, F.F.; Purba, L.D.A.; Riyadi, F.A., (2023). Application of Box-Behnken design to mineralization and color removal of palm oil mill effluent by electrocoagulation process. Environ Sci Pollut Res., 30(28): 71741–71753 **(12 pages).**
Rakhmania,; Kamyab, H.; Yuzir, M.A.; Riyadi, F.A.; Ostadrahimi, A.; Khademi, T.; Ghfar, A.A.; Kirpichnikova, I., (2022). Electrochemical oxidation of palm oil mill effluent using platinum as anode: Optimization using response surface methodology. Environ. Res., 214: 1-10 **(11 pages).**
Retnaningsih, U.O.; Asriwandari, H.; Ningsih, R.B.; Purwanti, I.T.; Sidiq, R.S.S.; Artina, D.; Rosaliza, M. (2022). The persistence of patriarchy in the palm oil sector: Evidence from the Riau Province of Indonesia. Cogent Soc. Sci., 8(1): 1-15 **(16 pages).**
Rhebergen, T.; Zingore, S.; Giller, K.E.; Frimpong, C.A.; Acheampong, K.; Ohipeni, F.T.; Panyin, E.K., Zutah, V.; Fairhurst, T., (2020). Closing yield gaps in oil palm production systems in Ghana through best management practices. Europ. J. Agron., 115: 1-19 **(19 pages).**
Rodthong, W.; Kuwornu, J.K.M.; Datta, A.; Anal, A.K.; Tsusaka, T.W., (2023). Farmers' perceptions and likelihood of adoption of the roundtable on sustainable palm oil practices in Thailand. Environ.

Dev., 47: 1-16 **(16 pages).**
Rofiq, M.N.; Martono, S.; Gopar, R.A., (2021). Increasing nutrient quality and in vitro digestibility of mixed feed oil palm waste for ruminant feed by solid-state fermentation technology. IOP Conference Series: Earth Environ. Sci., 637(1): 1-7 **(7 pages).**
Romero, H.M.; Daza, E.; Ayala-Díaz, I.; Ruiz-Romero, R., (2021). High-Oleic Palm Oil (HOPO) production from parthenocarpic fruits in oil palm interspecific hybrids using naphthalene acetic acid. Agronomy. 11(2): 1-37 **(37 pages).**
Rosenani, A.B.; Rovica, R.; Cheah, P.M.; Lim, C.T., (2016). Growth performance and nutrient uptake of oil palm seedling in prenursery stage as influenced by oil palm waste compost in growing media. Int. J. Agron., 2016: 1-8 **(8 pages).**
Saelor, S.; Kongjan, P.; Prasertsan, P.; Mamimin, C.; O-Thong, S., (2024). Enhancing the efficiency of high solid anaerobic digestion of empty fruit bunches under thermophilic conditions by particle size reduction and co-digestion with palm oil mill effluent. Carbon Resour. Convers., 1-12 (**12 pages**).
Siregar, E.S.; Sentosa, S.U.; Satrianto, A., (2024). An analysis on the economic development and deforestation. Global J. Environ. Sci. Manage., 10(1): 355–368 **(13 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).**
Sung, C.T.B., (2016). Availability, use, and removal of oil palm biomass in Indonesia. Int. Council Clean Transport., 1: 1-39 **(39 pages).**
Syahza, A.; Asmit, B., (2020). Development of palm oil sector and future challenge in Riau Province, Indonesia. J. Sci. Technol. Policy Manage., 11(2): 149–170 **(22 pages).**
Teng, S.; Khong, K.W.; Che Ha, N., (2020). Palm oil and its environmental impacts: A big data analytics study. J. Cleaner Product., 274: 1-13 **(13 pages).**
Tohiran, K.A.; Nobilly, F.; Zulkifli, R.; Ashton-Butt, A.; Azhar, B., (2019). Cattle-grazing in oil palm plantations sustainably controls understory vegetation. Agric. Ecosyst. Environ., (278): 54–60 **(7 pages).**
Tow, W.K.; Goh, A.P.T., Sundralingam, U.; Palanisamy, U.D.; Sivasothy, Y., (2021). Flavonoid composition and pharmacological properties of elaeis guineensis jacq. leaf extracts: A systematic review. Pharmaceuticals. 14(10): 1–20 **(20 pages).**
Uke, A.; Nakazono-Nagaoka, E.; Chuah, J.A.; Zain, N.A.A.; Amir, H.G.; Sudesh, K.; Abidin, N.Z.H.A.Z.; Hashim, Z.; Kosugi, A., (2021). Effect of decomposing oil palm trunk fibers on plant growth and soil microbial community composition. J. Environ. Manage., 295: 1-9 **(9 pages).**
Urugo, M.M.; Teka, T.A.; Teshome, P. G.; Tringo, T.T., (2021). Palm oil processing and controversies over its health effect: overview of positive and negative consequences. J. Oleo Sci., 70(12): 1693–1706 **(13 pages).**
Woittiez, L.S.; Wijk, M. T.: Slingerland, M., Noordwijk, M.V.; Giller, K. E., (2017). Yield gaps in oil palm: A quantitative review of contributing factors. Europ. J. Agron., 83: 57–77 (**21 pages**).
Xu, Y.; Yu, L.; Ciais, P.; Li, W.; Santoro, M.; Yang, H.; Gong, P., (2022). Recent expansion of oil palm plantations into carbon-rich forests. Nat. Sustainability. 5(7): 574–577 **(4 pages)**.
Zain, M.S.C.; Lee, S.Y.; Sarian, M.N.; Fakurazi, S.; Shaari, K., (2020). In vitro wound healing potential of flavonoid c-glycosides from oil palm (*Elaeis guineensis jacq.*) leaves on 3T3 fibroblast cells. Antioxidants. 9(4): 1-18 (**18 pages).**

AUTHOR (S) BIOSKETCHES

Ilhami, A., Ph.D. Candidate, Faculty of Mathematics and Natural Science, Universitas Pendidikan Indonesia, Jl. Dr. Setiabudhi No 229, Bandung, Indonesia
- Email: *aldevailhami@upi.edu*
- ORCID: 0000-0002-8160-8194
- Web of Science ResearcherID: AAY-4386-2020
- Scopus Author ID: 57207964619
- Homepage: https://tipaftk.uin-suska.ac.id/dtps-prodi-tadris-ipa/

Hidayat, T., Ph.D., Professor, Faculty of Mathematics and Natural Science, Universitas Pendidikan Indonesia, Jl. Dr. Setiabudhi No 229, Bandung, Indonesia.
- Email: *topikhidayat@upi.edu*
- ORCID: 0000-0002-4589-8059
- Web of Science ResearcherID: AEE-0031-2022
- Scopus Author ID: 57196476160
- Homepage: https://biologi.upi.edu/v2/?p=7905

Riandi, Ph.D., Professor, Faculty of Mathematics and Natural Science, Universitas Pendidikan Indonesia, Jl. Dr. Setiabudhi No 229, Bandung, Indonesia,
- Email: *riandi@upi.edu*
- ORCID: 0000-0003-4187-7338
- Web of Science ResearcherID: CAH-1841-2022
- Scopus Author ID: 57195056290
- Homepage: https://biologi.upi.edu/v2/?p=8060

HOW TO CITE THIS ARTICLE

Ilhami, A.; Hidayat, T.; Riandi, (2024). Exploring the potential of palm oil plantation waste for local communities. Global J. Environ. Sci. Manage., 10(SI): 219-236.

DOI: 10.22034/gjesm.2024.10.SI.14

URL: https://www.gjesm.net/article_714603.html

Global J. Environ. Sci. Manage. 10(SI): 237-250, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Bibliometric analysis of biochar application for environmental management in agricultural sector

B.A. Bakar[1], Idawanni[1,*], A. Azis[1], S. Kurniawati[1], Y. Giamerti[1], Yardha[1], R. Purba[1], S. Abdullah[1], Jonharnas[1], D.R. Mustikawati[1], W. Chiari[2], E.A. Wikurendra[3,4]

[1] *Research Center for Food Crops, National Research and Innovation Agency, Cibinong, Bogor 16911 Indonesia*

[2] *Division of Mathematical and Physical Sciences, Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa, Japan*

[3] *Department of Health Scieces , Faculty of Humanities and Health Sciences, Curtin University, Miri 98000, Malaysia*

[4] *Doctoral School of Management and Organizational Sciece, Hungarian University of Agriculture and Life Science, Kaposvar 7400 Hungary*

ARTICLE INFO

Article History:
Received 06 May 2024
Revised 12 July 2024
Accepted 17 September 2024

Keywords:
Agriculture
Biochar
Bibliometric analysis
Environmental management
Soil fertility
Sustainability.

ABSTRACT

BACKGROUND AND OBJECTIVES: Biochar has gained prominence as a sustainable solution in agriculture and environmental management, with benefits of enhancing soil fertility, improving crop yield, and mitigating the climate change. This study sought to conduct a bibliometric analysis of biochar research within the context of agricultural applications, with the objective of evaluating its progression, thematic development, and patterns of global collaboration.

METHODS: A search was conducted in the Scopus database on September 1, 2024 using a pre-determined keyword combination. The retrieved data were analyzed using the Bibliometrix package in RStudio to evaluate publication trends, research theme evolution, and international collaboration networks. The authors' keywords were employed in a co-occurrence analysis to discern principal research themes and their interrelations. The analysis on research theme evolution utilized a single time split, dividing the datasets into 2006–2021 and 2022–2025. The collaboration network was established with a minimum edge threshold of 4, and it is illustrated in a mapped format.

FINDINGS: The search using a predetermined keyword combination identified 4,402 publications related to biochar, with 2,857 focused specifically on its application in agriculture. A pronounced increase in research output was observed after 2016. China is spearheading the investigation in this domain, having produced 1,319 publications from individual countries and 564 from various international collaborations. In the second leading position, the United States has produced 382 publications, where 101 of which were published along with authors from other countries. The thematic analysis revealed a transition from the original focal points, which included carbon sequestration, to newly emerging subjects such as microbial biomass and the remediation of heavy metals.

CONCLUSION: There is an increasing significance of biochar research worldwide, where the thematic evolution and patterns of international collaborations have been successfully synthesized in this study. The thematic shifts suggest the growing interest in microbial biomass and heavy metal remediation-related themes, indicating the multiple applications of biochar in both environmental management and agricultural productivity. Given the robust framework of international research collaboration, it is essential to undertake a unified global initiative aimed at standardizing biochar application techniques, enhancing production processes, and evaluating the long-term effects of biochar usage. The production and utility of biochar in agricultural sector could be optimized through international collaboration and policy development aiming to improve soil health, and subsequently food security. The study has effectively mapped the landscape of biochar studies within the realm of environmental management, with a particular focus on its roles in enhancing microbial biomass and remediating heavy metal contamination.

DOI: 10.22034/gjesm.2024.10.SI.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
35	6	0

*Corresponding Author:
Email: *idaw001@brin.go.id*
Phone: +8526 0019 973
ORCID: 0000-0002-8466-7421

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Biochar, a carbon-rich material derived from the pyrolysis of organic biomass, has been recognized as a promising soil amendment with significant potential to enhance agricultural productivity. A meta-analysis revealed that the incorporation of biochar in agricultural practice increased the production up to 25.3 percent (%) ± 3.2% (Bai *et al*., 2022). The enhancement in productivity has been linked to the augmented soil fertility, enhanced water retention capabilities, and improved nutrient retention that result from the incorporation of biochar (Allohverdi *et al*., 2021). Studies have demonstrated that the addition of biochar can produce an average increase in crop yields of approximately 16%, with a remarkable 40% improvement observed specifically in acidic soil environments (Schmidt *et al*., 2021). As indicated in a recent meta-analysis, biochar application can lead to a significant increase in grain yield, depending on the biochar types (Schmidt *et al*., 2021). Biochars derived from poultry litter have been reported to demonstrate yield improvements of up to 28% (Schmidt *et al*., 2021). Beyond the selection of feedstock, the performance of biochar is influenced by the parameters of pyrolysis as well as the inherent properties of the soil (Gao *et al*., 2021). Earlier research has demonstrated that the efficacy of biochar produced from sewage sludge is contingent upon the temperatures at which pyrolysis occurs (de Figueiredo *et al*., 2020).The effect of biochar incorporation is not only on nutrient retention, but also various aspects of plant growth and soil health. Previously, biochar was found to increase soil water-holding capacity by up to 30%, enhance soil microbial activity, and improve soil bulk density and porosity (Adhikari *et al*., 2022; Pokharel *et al*., 2020). Recent systematic reviews and meta-analyses have consistently highlighted the positive impacts of biochar, indicating an average increase in crop yields of 16%, with some studies reporting enhancements of up to 40% in acidic soil conditions (Schmidt *et al*., 2021). Biochar has been found to enhance root growth, increasing root biomass by 32% and root surface area by 39% (Chew *et al*., 2020). These effects contribute to more effective nutrient uptake and strengthen plant resilience, particularly in soils that are low in nutrients. Moreover, biochar positively affects key physiological parameters in plants, such as the rate of photosynthesis and water use efficiency (He *et al*., 2020). Additionally, biochar's ability to sequester carbon makes it a valuable tool for carbon dioxide removal (CDR) strategies, which is beneficial for environmental management (Luo *et al*., 2023). Biochar is recognized as a sustainable solution, valued for its role in recycling agricultural waste into a useful product (Sumiyati *et al*., 2024). This examination offers valuable insights that not only pinpoint the most significant research contributions and reveal deficiencies in the existing literature but also emphasize nascent areas of inquiry, thereby influencing the trajectory of forthcoming research initiatives(Ahmad and Chiari, 2023; Zulkifli *et al*., 2023). The bibliometric analysis employs multiple, complex statistical methods, including co-occurrence network analysis and thematic evolution, to uncover publication trends, thematic development, and collaboration patterns. In the realm of co-occurrence network analysis, the frequency and relationships of terms or keywords are scrutinized, leading to the development of visual networks that elucidate the predominant concepts within the field. Thematic evolution analysis further tracks the prevalence and development of research topics over time, using techniques like latent dirichlet allocation (LDA) or non-negative matrix factorization (NMF) (Aria and Cuccurullo, 2017). This analysis provides insights that not only identify the most impactful research and highlight gaps within the literature but also draw attention to emerging fields of study, thereby shaping the direction of future research endeavors. By aligning with global trends and challenges, these findings can help researchers and policymakers focus biochar development on the most promising and impactful trajectories (Ginting *et al*., 2023; Iqhrammullah *et al*., 2023). Previously, for instance, the bibliometric analysis on microalgae research revealed the most prominent research topics such as biofuel production, wastewater treatment, and environmental sustainability (Zhang *et al*., 2020). Within agricultural studies, bibliometric methods have been utilized to investigate the impact of digitalization on agricultural practices (Bertoglio *et al*., 2021; Latino *et al*., 2022). Whilst there are review articles on biochar utility in agriculture (Wang and Wang, 2019; Xie *et al*., 2022), the bibliometric analysis has not been performed. The execution of a bibliometric analysis to methodically assess the research landscape holds significant importance, particularly due to the wide-

ranging applicability of biochar in numerous fields (Wang and Wang, 2019). Herein, the aim of the study was to conduct a bibliometric analysis of biochar research in agricultural sector. Results from the study are expected to offer insights into the evolution of biochar research and its potential to address the pressing challenges of modern agriculture. The study was conducted in Banda Aceh, Indonesia, in 2024.

MATERALS AND METHODS

The bibliometric analysis of biochar research in agriculture was conducted using the Bibliometrix package in RStudio. A systematic search was performed using the Scopus database with the keywords (TITLE: biochar) AND TITLE-ABS-KEY: agriculture OR crop). There were no constraints placed on the type of document or the year of publication during the search. The criteria for inclusion mandated that the document must include "biochar" in the title, as well as "agriculture" or "crop" in the title, abstract, or keywords. The retrieved data were exported from Scopus as a .csv (comma separated values) file and analyzed in RStudio using the Bibliometrix package, following the suggestion form a previous study (Aria and Cuccurullo, 2017). An assessment of publication trends was performed to elucidate the evolution and dispersion of research over time. The publication trends were also observed for each affiliation to identify the most relevant institution in this topic. Co-occurrence analysis was conducted based on the authors' keywords to identify key research themes and their interconnections. This study presents a schematic representation of the relationships between different topics in the literature, enabling the discernment of key and developing themes within the field. Thematic shift analysis was performed using a single time split, which divided the dataset into two periods (2006-2021 and 2022-2025) to track the evolution of research focus areas over time. This methodology facilitates the detection of changes in thematic emphasis and the development of novel research domains. An international collaboration map was created to illustrate global research partnerships. The analysis was conducted with a minimum edge of 4, focusing on collaborations with at least four joint publications. In Bibliometrix, co-occurrence network analysis and thematic evolution are generated by complex statistical methods. The initial step in co-occurrence network analysis involves conducting a frequency analysis, wherein the occurrences of terms or keywords within the dataset are quantified. Subsequently, a co-occurrence matrix is developed, which captures the frequency with which pairs of terms co-appear in the same documents. The matrix is then used to create visual networks using algorithms like the Force-Directed Layout, which positions nodes (terms) based on their relationships and connection strengths. Measures of centrality, such as Degree Centrality and Betweenness Centrality, are applied to ascertain the most significant terms in the network. In thematic evolution analysis, techniques like LDA or NMF are used to extract and model topics from the literature.

RESULTS AND DISCUSSION

Publication trends

ibliometric approaches were employed to analyze meta-data from a dataset comprising 5,363 entries. The publication trends concerning the application of biochar in agricultural research are represented in Fig. 1. A significant growth in the number of publications related to biochar research in agriculture over the past two decades was observed. The number of publications has increased exponentially, where the adjusted-coefficient of determination (R^2) was found to be 0.995. The remarkably elevated R^2 value indicates that the exponential rise in biochar research is not merely a coincidental phenomenon; rather, it reflects a consistent and foreseeable expansion, propelled by the growing acknowledgment of biochar's significance in agricultural practices and environmental stewardship. The data shows a gradual rise in publications from 2006 (only 2 publications) to a peak in 2023 (819 publications). By comparison, the prior bibliometric study on the utilization of drones in agricultural practices revealed a dramatic surge in publications, increasing from 108 in 2013 to 1,275 in 2020 (Rejeb *et al*., 2022). As compared to newer topics such as agriculture 4.0, the publications growth was observed to be less stable where it was only 2 studies published in 2002 and increased to 126 studies in 126 (Mühl and de Oliveira, 2022). Original research articles comprised the largest share of the documents, representing 82.1%. In contrast, reviews made up 8.2%, while conference papers and book chapters accounted for 5% and 3.7%, respectively. Other types of publications, such as errata, books, notes, retracted articles, letters, editorials, data

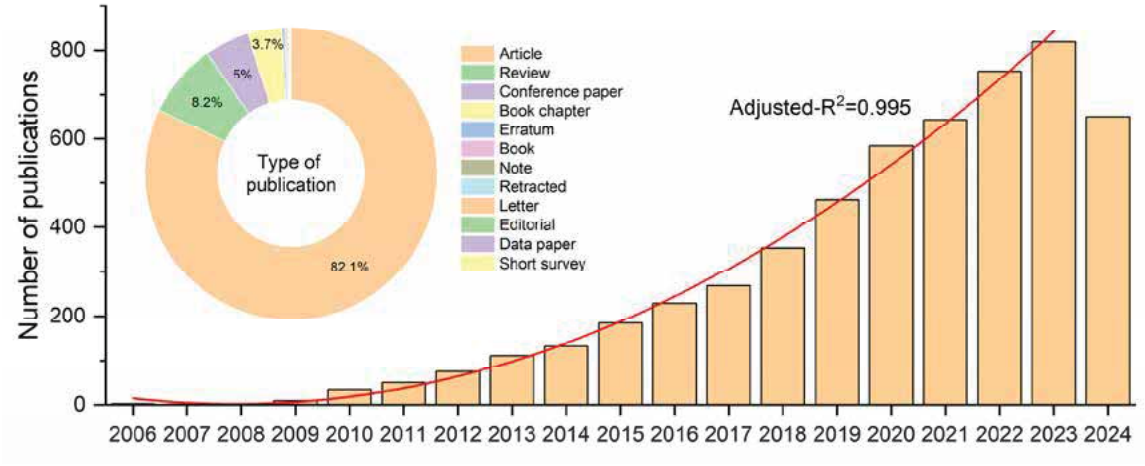


Fig. 1: Number of publications based on the publication year and type. The graph was generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al*., 2024)

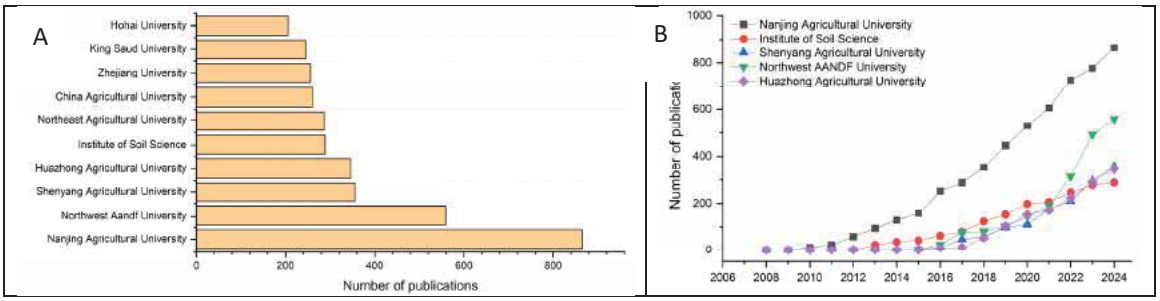


Fig. 2: Most relevant affiliations (A) and their annual publication trends (B) in biochar research for agricultural applications. The graphs were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al*., 2024)

papers, and short surveys, each constituted less than 1% of the total output.

The analysis of affiliations and publication trends are presented in Fig. 2. Nanjing Agricultural University revealed as the leading institution in biochar research for agricultural applications, with a substantial increase in the number of publications from 13 publications (in 2010) to 865 publications (in 2024). Northwest A and F University follows with 559 publications, showing a significant growth since 2016. In the year 2024, Shenyang Agricultural University, Huazhong Agricultural University, and the Institute of Soil Science have significantly advanced the field with their respective outputs of 356, 346, and 289 publications. Additionally, China Agricultural University, Zhejiang University, King Saud University, and Hohai University have published between 206 and 261 articles. The evidence presented indicates that a select group of influential institutions, notably in China, are at the helm of biochar research related to agriculture, with Nanjing Agricultural University emerging as a leader in this area.

Research trend

Research trend based on the co-occurrence of author's keywords is presented in Fig. 3. A review of the keywords relevant to biochar research in agriculture demonstrates that "biochar" is the most extensively investigated topic, with a substantial count of 2,857 publications. Other prominent keywords include "pyrolysis" (323 publications), "soil amendment" (186 publications), and "carbon sequestration" (181 publications). Topics such as "adsorption" and "soil" also appear frequently, with

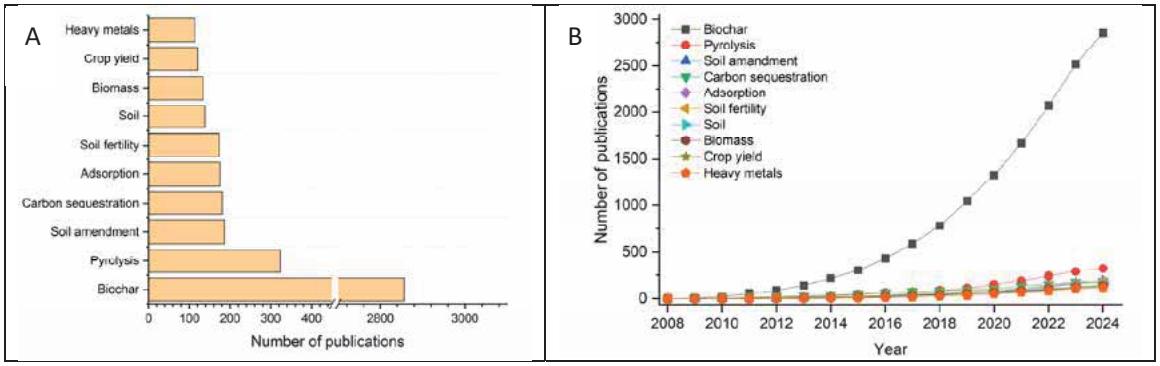


Fig. 3: Most relevant keywords (A) and their annual trend in publications (B) relevant to agricultural application of biochar research. The graphs were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al*., 2024)

176 and 139 publications, respectively. A total of 174 publications have incorporated the keyword "soil fertility," reflecting its widespread relevance in academic discourse. In comparison, the areas of "biomass" and "heavy metals" have been the focus of 134 and 114 publications, respectively, indicating a lower frequency of study. The analysis also reveals that there are at least 121 publications focusing on the effect of biochar amendment, as indicated by the occurrence of keyword "crop yield". As for keyword "plant growth", indicative to agricultural crop growth, was identified in 73 publications. The trend analysis from 2008 to 2024 shows a significant increase in publications related to biochar, with a marked rise after 2016. The increase in interest underscores the rising appreciation for the environmental and agricultural benefits that biochar offers. Historically, the term "charcoal" was widely utilized, especially in contexts related to fuel and metalworking. However, as research shifted toward environmental sustainability and soil management, "biochar" became the preferred term, emphasizing its role as a soil amendment and its potential for carbon sequestration. Although there has been a notable rise in the number of publications addressing areas such as pyrolysis, soil amendment, and carbon sequestration, this growth has occurred at a more measured pace compared to the accelerated development of studies focused on biochar. These findings indicate a strong and growing interest in biochar and its applications, with related topics experiencing steady, albeit slower, growth. This trend indicates the shifted focus of biochar research from its general applications to the specialized and environmentally significant role of biochar in agriculture.

The co-occurrence network reveals several distinct clusters, each representing interconnected research themes (Fig. 4a). The green cluster is predominantly focused on environmental themes, including "greenhouse gas," "nitrogen fertilizers," and "soil carbon," highlighting the role of biochar in mitigating emissions and improving soil nutrient management. Centered around agricultural applications, the blue cluster features keywords including "crop yield," "fertilizer," and "soil moisture." This highlights a considerable interest in exploring the influence of biochar on enhancing agricultural productivity and improving soil health. The red cluster addresses technical aspects, such as "pyrolysis," "adsorption," and "surface area," which are critical for understanding the production and physical properties of biochar. Finally, the purple cluster is concerned with pollution and remediation, emphasizing biochar's potential in addressing soil contamination and environmental cleanup (Fig. 4a). This thematic plot additionally organizes these themes by their progression and importance, wherein the produced plot is illustrated in Fig. 5a. "Biochar," "charcoal," and "soils" are identified as motor themes, which are both well-developed and central to the field, driving much of the research activity. Conversely, themes such as "soil pollution" are categorized as fundamental themes, essential to the discipline yet lacking in specialization. Niche themes, including "adsorption" and potential of hydrogen ("pH") represent highly specialized areas that, while important, are less central to the broader research community. The concepts of "crop yield" and "carbon sequestration" reflect emerging

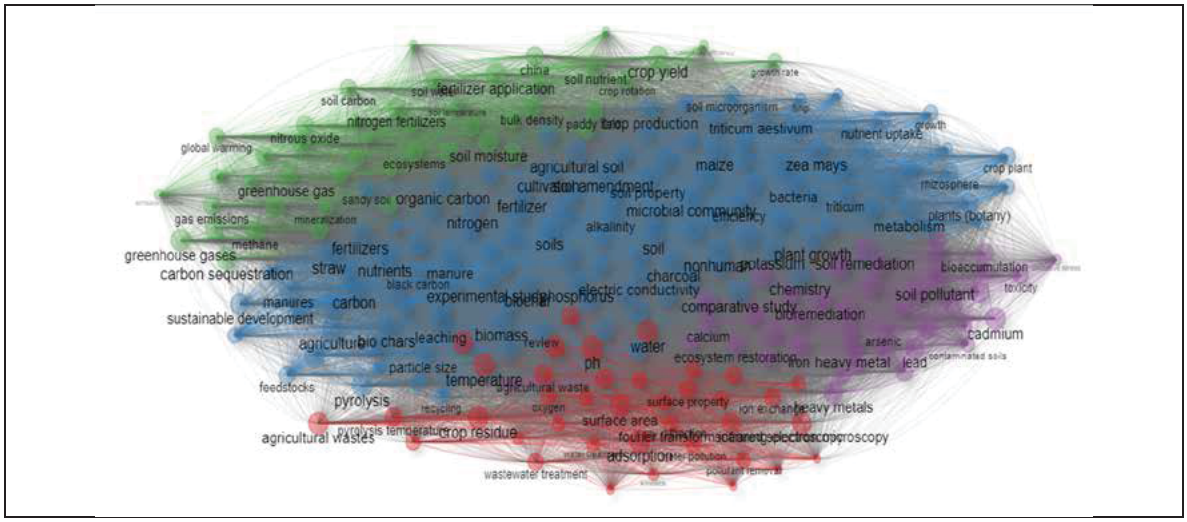


Fig. 4: Co-occurrence network (a) of research on biochar application in agriculture. The graphs were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al*., 2024)

or diminishing trends, pointing to domains that are undergoing significant transformations, either increasing in importance or fading from prominence.

Evolution of key research themes in biochar studies from 2006-2021 to 2022-2025 was illustrated in a Sankey diagram and presented in Fig. 5b. The extent of the bands that associate themes throughout various periods illustrates the comparative importance and ongoing nature of these themes. The wider the band, the more significant and consistent the theme is across the periods. Biochar consistently exhibits the widest band, which statistically indicates its unchanging prominence in research. Conversely, topics such as nitrous oxide and carbon sequestration display more restricted ranges as they progress into the 2022-2025 timeframe, indicating a potential decrease in research emphasis or their assimilation into broader, emerging themes. The appearance of new themes with significant band width in the 2022-2025 period (such as microbial biomass, soil moisture) suggests a statistically significant shift in research priorities, indicating new or evolving areas of interest within the field of biochar research. In the earlier timeframe spanning from 2006 to 2021, the prevailing themes encompassed “biochar,” “nitrous oxide,” “carbon sequestration,” “adsorption,” and “pyrolysis.” As research has progressed into the 2022-2025 period, there has been a noticeable shift and expansion in focusAlthough “biochar” remains a predominant subject of study, recent investigations have expanded to encompass new topics such as “microbial biomass,” “soil moisture,” and “heavy metals.” In addition, “maize” has surfaced as a critical area of focus, highlighting the rising interest in the utilization of biochar in relation to specific crop production systems. Themes like “carbon sequestration” and “nitrous oxide,” which were prominent in earlier years, appear to have been integrated into broader studies or have shifted focus as indicated by their reduced prominence in the current thematic landscape. This shift in research themes illustrates the evolving landscape of biochar investigation, marked by an enhanced attention to its biological implications and its practical applications within the realms of agriculture and environmental management.

Collaboration trends

The analysis of publication data reveals that China is leading the biochar research with a significant number of publications, totaling 1,319 from single-country studies and 564 from international collaborations (Fig. 6a). Following closely is the United States, which has generated 281 publications from research conducted independently and 101 from collaborative projects. India also exhibits significant research productivity, contributing 236 publications from single-country research and 63 from collaborative endeavors. Other

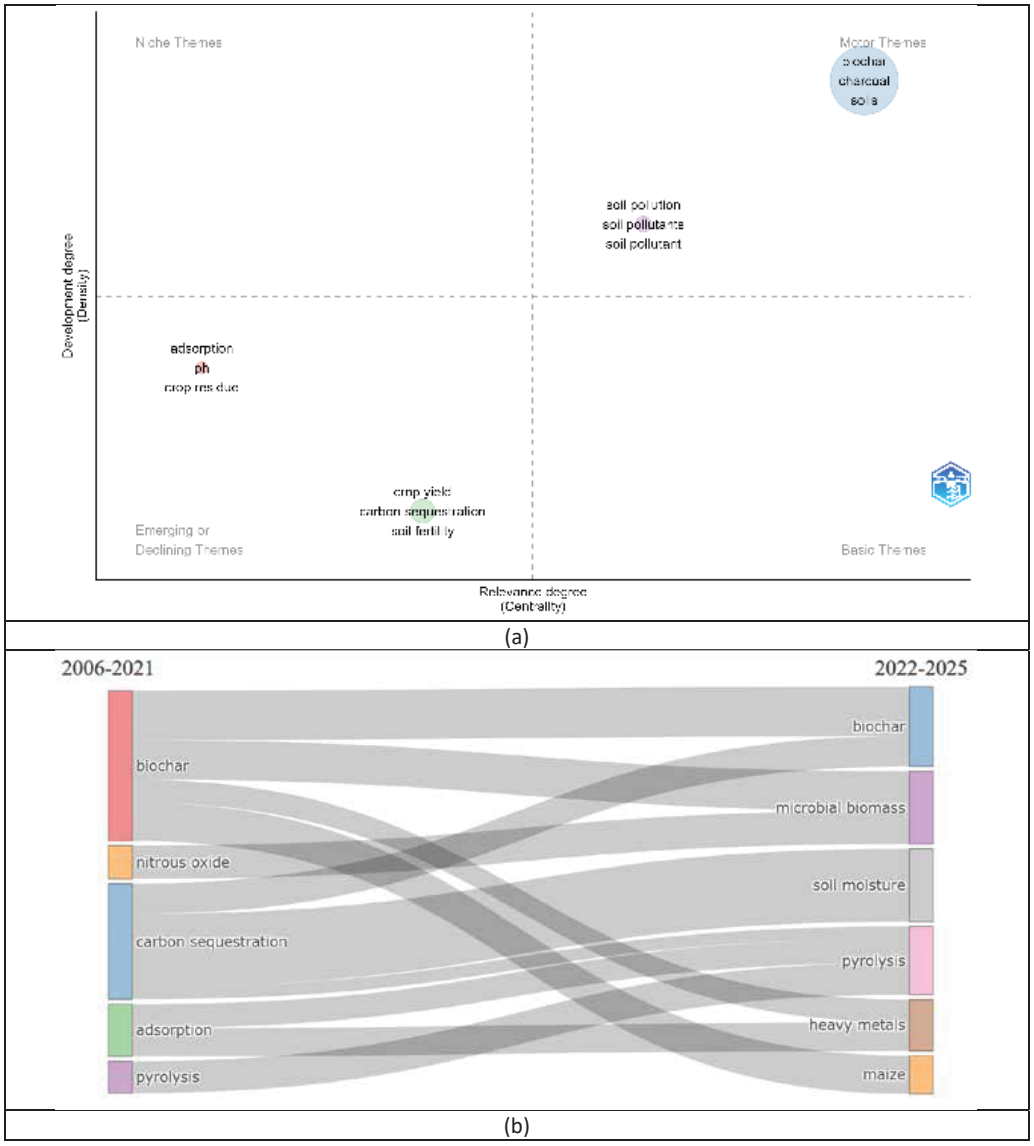


Fig. 5: Thematic plot (a) and thematic evolution plot (b) of research on biochar application in agriculture. The graphs were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al*., 2024)

countries with notable contributions include Pakistan, Italy, and Australia, which have higher proportions of publications from international collaborations compared to their single-country outputs. Particularly in Pakistan, the collaborative publications exceed single-country publications. In contrast, countries like Indonesia, Nigeria, and Thailand have a higher focus on single-country research, with limited international collaboration. For example, Indonesia has 80 single-country publications and only 6 collaborative ones. Another example, Thailand has 47 single-country publications and just 6 collaborative ones (Fig. 6a). According to a previous bibliometric study focused on biochar research, China emerged as the dominant contributor, with 227 published studies, which constituted 51.01% of the total number of publications (Wang *et al.,* 2024). The map of global research collaborations in biochar studies reveals a

dense network of international partnerships, with China and the United States emerging as central hubs (Fig. 5b). China, with 564 international collaborations, notably collaborates frequently with the United States (190 collaborations), Australia (142 collaborations), Korea (60 collaborations), and Saudi Arabia (70 collaborations). The United States demonstrates robust collaborative relationships with a variety of nations, having established 101 partnerships with China, 56 with Canada, 29 with Germany, and 29 with Australia. Other countries such as Australia, the United Kingdom, and Germany also play significant roles in fostering international research partnerships, contributing to a globally interconnected research landscape. To illustrate, Australia boasts 101 collaborative initiatives with the United States, 28 with Korea, and 24 with Saudi Arabia. Conversely, Germany has 48 partnerships with China and 29 with the United States. Countries like Pakistan, with 123 collaborations, India (63 collaborations), and Brazil (43 collaborations) also demonstrate active participation in global research networks, often collaborating with leading research

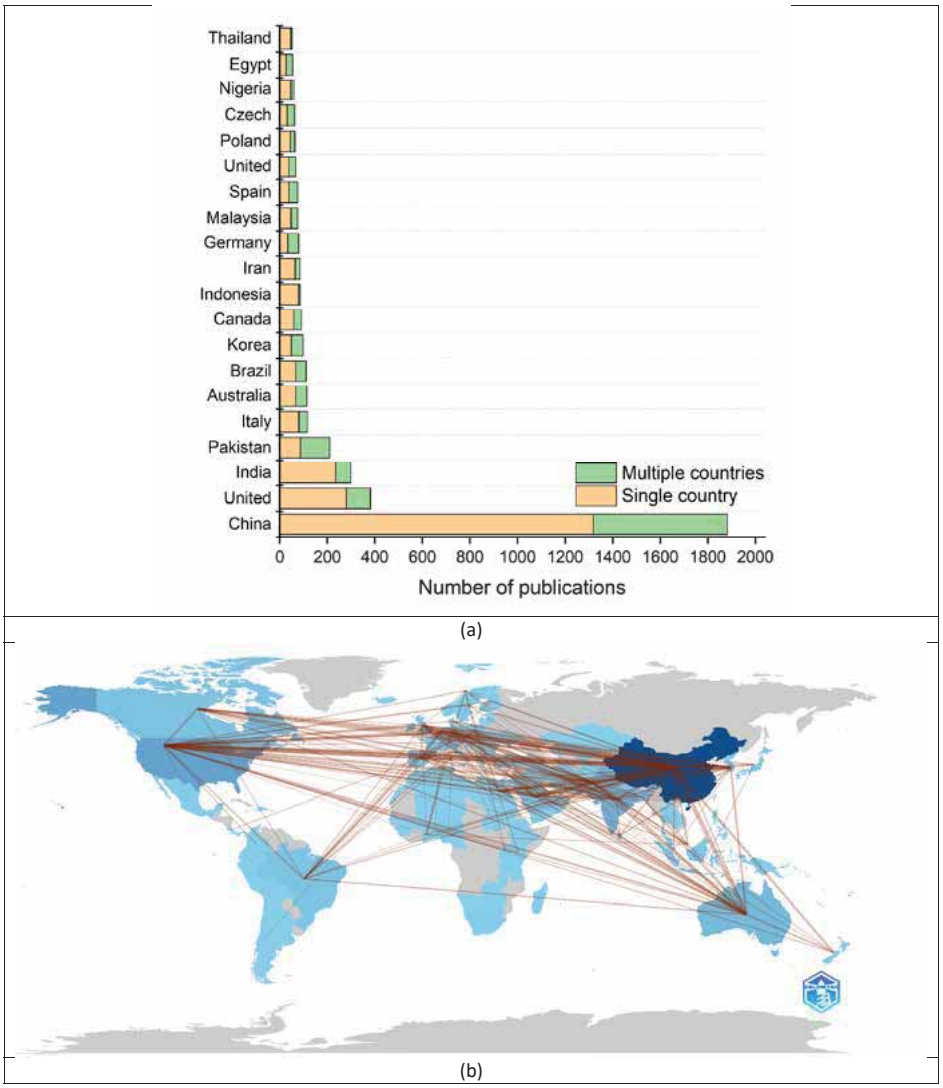


Fig. 6: Number of publications from each corresponding author's country (a). The collaboration between countries as illustrated in a map (b). The graph and collaboration map were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al*., 2024)

nations. Collaborative research network of China is 5.6 times larger than that of Indonesia and 3.5 times larger than that of Pakistan. China's collaboration rate of 29.9% signifies a harmonious balance between leveraging domestic research strengths and fostering international partnerships. Meanwhile, the United States, with a collaboration rate of 26.4%, demonstrates a similar pattern, although it shows a slightly stronger inclination towards domestic research efforts (Fig. 5b).

Trends in the biochar research and their implications

The bibliometric analysis of biochar research within the context of agricultural applications has demonstrated a notable surge in academic publications, especially following the year 2016, characterized by an exponential growth in the volume of research output. This growth reflects the increasing recognition of biochar's potential to address pressing challenges in agriculture, such as soil fertility, carbon sequestration, and environmental sustainability. Findings from the present study align with previous literature that highlights biochar's ability to improve crop yields, enhance soil properties, and mitigate climate change through CDR (Neogi *et al*., 2022). In the agricultural domain, the requisite quantity of biochar generally falls within the range of 5 to 30 tons per hectare, influenced by the intended improvements in soil attributes and the resultant crop yield (Bai *et al*., 2022). Biochar improves soil fertility through its high surface area and porous structure, which increases soil aeration and water retention. This structure also provides a habitat for beneficial microorganisms, enhancing microbial activity and nutrient cycling. Furthermore, biochar contributes to an increase in the cation exchange capacity of soil, facilitating the retention of key nutrients including potassium, calcium, and magnesium, which are critical for optimal plant development (Allohverdi *et al*., 2021). The impact of biochar addition to the soil has been previously highlighted to alter the presence of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) contents in the soil (Shalini *et al*., 2021). Biochar plays a significant role in curbing greenhouse gas emissions by interfering with the nitrification and denitrification processes present in the soil ecosystem (Neogi *et al*., 2022; Shalini *et al*., 2021). By acknowledging the trend in biochar research focused on reducing greenhouse gas emissions, related stakeholders can develop practical guidelines for such purposes. A recent meta-analyses have shown that biochar can increase crop yields by up to 16%, with even greater effects in acidic soils (Schmidt *et al*., 2021). Specifically, the increased yield has been reported in various crops such as maize (Liu *et al*., 2021), legumes (Farhangi-Abriz *et al*., 2021), and rice (Liu *et al*., 2022). This current study illustrates a significant transformation in the thematic focus of biochar research, demonstrating a temporal shift towards emerging areas of interest, including microbial biomass, soil moisture, and heavy metal interactions. The transition from earlier research themes, such as nitrous oxide and carbon sequestration, reflects an enhanced understanding of the complex roles that biochar plays in soil ecosystems. The shifted focus is driven by the motivation to study applicability of biochar in which becoming more evident. These emerging themes align with global priorities in combating soil degradation and pollution, which are often linked to funding opportunities from both governmental and international agencies. Initially, research centered on the fundamental properties and environmental benefits of biochar, such as its ability to sequester carbon and reduce greenhouse gas emissions. As the discipline evolved, scholars started to investigate more targeted applications and interactions within soil ecosystems. This shift resulted in the development of themes concerning the biological effects of biochar, including its role in increasing microbial biomass and its utility in regulating soil moisture and addressing heavy metal contamination. Recent publications have reported that biochar could increase the soil microbial biomass (Li *et al*., 2020). Morever, studies revealed that the effectiveness of biochar is dependent to the soil moisture levels (Dissanayake *et al*., 2022). In its intersection with heavy metal, biochar application has been reported to stabilize the lead (Pb) content, thus preventing its translocation to the crops (Boostani *et al*., 2021). In the context of sustainable agriculture, biochar serves a vital function by enriching soil fertility, enhancing the capacity for water retention, increasing microbial biomass, and mitigating the effects of heavy metal pollution. Based on the bibliometric findings, these benefits are evidenced by the thematic shifts in research focus towards biochar's application in improving soil health and addressing environmental contamination, reflecting its growing importance in sustainable

agriculture and environmental management. Herein, the analysis of global collaboration trends indicates that both China and the United States serve as pivotal centers in the field of biochar research, participating in a multitude of international partnerships. China, with 564 collaborations, and the United States, with 101 collaborations, frequently partner with each other and other countries, fostering a globally interconnected research network. These patterns can be explained by the strategic importance of biochar research in addressing global challenges like food security and climate change, which necessitates collaborative efforts across borders. The development of these collaborative networks is likely influenced by the imperative to share resources, expertise, and information, thereby empowering researchers to more effectively confront complex, multidisciplinary problems. Countries with emerging economies, such as India and Brazil, are increasingly participating in these networks, contributing to the global knowledge pool and benefiting from the collaborative research environment. In previous research, the leading countries in the research include China and the United States (Chiari *et al*., 2022; Puspita *et al*., 2022; Pratama *et al*., 2024). Within the field of agricultural studies India and Brazil have emerged as leaders in research development, as reflected by the substantial increase in publication output, especially in the case of Brazil, which has experienced a particularly swift escalation (Bertoglio *et al*., 2021; Rejeb *et al*., 2022; Mühl and de Oliveira, 2022).

Limitations

Interpretation of the findings from the present bibliometric analysis should consider of its several limitations. Initially, the scope of the analysis was confined to publications listed in the Scopus database. While this database is comprehensive, it may not encompass all pertinent research, especially that which originates from non-English-speaking countries or smaller regional journals. Second, the study did not evaluate the quality or impact of the publications, instead prioritizing the quantity of publications and the nature of collaborative efforts. Finally, the thematic evolution was based on keyword analysis, which might oversimplify the complexity of the research themes. A more nuanced approach, possibly involving full-text analysis, could provide deeper insights into the evolution of biochar research.

CONCLUSION

The bibliometric analysis has successfully elucidated the evolution and current state of biochar research in agricultural applications. A unique contribution of this study does not only include the growth mapping and thematic shifts in biochar research since 2016 but also by revealing the impact of international collaborations on advancing biochar technologies. The study demonstrated a significant escalation in the number of publications, particularly since 2016, along with a thematic evolution from core environmental benefits like carbon sequestration to more targeted applications, such as the enhancement of microbial biomass and the remediation of heavy metals. The study reveals the central roles of China and the United States in driving global research collaborations, while also illustrating the expanding involvement of emerging economies like India and Brazil. The findings underscore the scientific value of international research networks in facilitating innovations in biochar technology and its application in diverse contexts. The findings of this study demonstrate that biochar is increasingly viewed not just as a method for improving soil conditions and crop yields, but also as a significant contributor to overarching environmental sustainability goals, which involve climate change mitigation and the restoration of ecological systems.. The thematic shift observed in the study underscores the dynamic nature of biochar research, with emerging focus areas such as soil moisture management and pollution remediation reflecting the evolving challenges in agricultural and environmental managementAs the scope of research broadens, the imperative to understand the long-term consequences of biochar use in diverse ecological and agricultural contexts intensifies. Researchers are encouraged to engage in interdisciplinary collaborations that integrate scientific, economic, and social perspectives, ensuring that biochar technologies are both effective and equitable. It is imperative to conduct more research on the socio-economic ramifications of biochar applications, particularly in smallholder farming contexts and resource-limited areas, to facilitate the equitable distribution of biochar's benefits across all communities. This bibliometric analysis yields findings that are crucial for policymakers, allowing them to keep pace with global trends and challenges in sustainable agriculture. Such insights are essential

for the formulation of policies that support the development of biochar technology along suitable pathways. It ensures that policy decisions are informed by the latest research, supporting the adoption of biochar in practices that address critical environmental and agricultural needs. According to the findings, it is projected that governmental support will play a crucial role in promoting the development of biochar research. Supportive policies and targeted funding are essential to scale up biochar applications, particularly in regions vulnerable to soil degradation, food insecurity, and climate change impacts. Governments should consider integrating biochar into national and regional sustainability strategies, promoting its use as part of broader efforts to achieve carbon neutrality and enhance soil resilience. Moreover, the facilitation of international collaborations via strategic policy frameworks and dedicated research funding can significantly harness global expertise. This strategy is essential for advancing innovation and ensuring that biochar research is aligned with addressing environmental challenges on both local and international scales.

AUTHOR CONTRIBUTIONS

B.A. Bakar contributed in the conceptualization, investigation, and writing of the original manuscript. Idawanni contributed in the conceptualization, investigation, and writing of the original manuscript. Yardha, contributed in supervisión, validation, and writing of the revision. R. Purba contributed in supervision, validation, and writing of the revision. S. Abdullah, contributed in supervision, validation, and writing of the revision. Jonharnas contributed in supervision, validation, and writing of the revision. A. Azis contributed in formal analysis, data presentation, and writing of the revision. S. Kurniawati contributed in formal analysis, data presentation, and writing of the revision. Y. Giamerti contributed in data presentation and writing of the revision. D.R. Mustikawati contributed in data presentation and writing of the revision. W. Chiari contributed in investigation. E.A. Wikurendra contributed in investigation and formal analysis.

ACKNOWLEDGEMENT

The authors appreciate the support from the National Research and Innovation Agency (BRIN) in facilitating the research and the preparation of this article. The study received no external funding.

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

©2024 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
AND	Boolean operator to limit the search
Bibliometrix	An RStudio package for bibliometric analysis
CDR	Carbon dioxide removal
CH_4	Methane
CO_2	Carbon dioxide
CSV	Comma separating value
Fig.	Figure
LDA	Latent dirichlet allocation
NMF	Non-negative matrix factorization

N_2O	Nitrous oxide
OR	Boolean operator to expand the search
Pb	Lead
pH	Potential of hydrogen
R^2	Coefficient of determination
Rstudio	A software used to compute R programming language
Scopus	Journal indexing database
TITLE	The search on the titles of published articles
TITLE-ABS-KEY	The search on the titles, abstracts, and keywords of published articles

REFERENCES

Adhikari, S.; Timms, W.; Mahmud M.P., (2022). Optimising water holding capacity and hydrophobicity of biochar for soil amendment–A review. Sci. Total Environ., 851(Part 1): 158043 **(15 pages)**.

Ahmad, K.; Chiari, W., (2023). Metal oxide/chitosan composite for organic pollutants removal: A comprehensive review with bibliometric análisis. Narra X., 1(2): e91 **(16 pages)**.

Allohverdi, T.; Mohanty, A.K.; Roy, P.; Misra, M., (2021). A review on current status of biochar uses in agricultura. Molecules. 26(18):5584 **(17 pages)**.

Aria, M.; Cuccurullo, C., (2017) Bibliometrix: An R-tool for comprehensive science mapping analisis. J. Informetr., 11(4): 959-975 **(17 pages)**.

Bai, S.H.; Omidvar, N.; Gallart, M.; Kämper, W.; Tahmasbian, I.; Farrar, M. B.; Singh, K.; Zhou, G.; Muqaddas, B.; Xu, C.-Y.; Koech, R.; Li, Y.; Nguyen, T. T. N.; van Zwieten, L., (2022). Combined effects of biochar and fertilizer applications on yield: A review and meta-analysis, Sci. Total Environ., 808: 152073 **(8 pages)**.

Bertoglio, R.; Corbo, C.; Renga, F.M.; Matteucci, M., (2021). The digital agricultural revolution: a bibliometric analysis literature review. IEEE Access, 9: 134762-134782 **(21 pages)**.

Boostani, H.R.; Hardie, A.G.; Najafi-Ghiri, M.; Khalili, D., (2021). The effect of soil moisture regime and biochar application on lead (Pb) stabilization in a contaminated soil. Ecotoxicol. Environ. Saf., 208: 111626 **(9 pages)**.

Chew, J.; Zhu, L.; Nielsen, S.; Graber, E.; Mitchell, D.R.; Horvat, J.; Mohammed, M.; Liu, M.; van Zwieten, L.; Donne, S.; Munroe, P.; Taherymoosavi, S.; Pace, B.; Rawal, A.; Hook, J.; Marjo, C.; Thomas, D.S.; Pan, G.; Li, L.; Bian, R.; Fan, X., (2020). Biochar-based fertilizer: supercharging root membrane potential and biomass yield of rice. Sci. Total Environ., 713:136431 **(11 pages)**.

Chiari, W.; Damayanti, R.; Harapan, H.; Puspita, K.; Saiful, S.; Rahmi, R.; Rizki, D.R.; Iqhrammullah, M., (2022). Trend of polymer research related to COVID-19 pandemic: Bibliometric análysis. Polymers. 14(16): 3297 **(14 pages)**.

de Figueiredo, C.C.; Pinheiro, T.D.; de Oliveira, L.E.Z.; de Araujo, A.S.; Coser, T.R.; Paz-Ferreiro, J., (2020). Direct and residual effect of biochar derived from biosolids on soil phosphorus pools: A four-year field assessment. Sci. Total Environ., 739:140013 **(10 pages)**.

Dissanayake, P.D.; Palansooriya, K. N.; Sang, M. K.; Oh, D.X.; Park, J.; Hwang, S.Y.; Igalavithana, A.D.; Gu, C.; Ok, Y.S., (2022). Combined effect of biochar and soil moisture on soil chemical properties and microbial community composition in microplastic-contaminated agricultural soil. Soil Use Manage., 38(3): 1446-1458 **(13 pages)**.

Farhangi-Abriz, S.; Torabian, S.; Qin, R.; Noulas, C.; Lu, Y.; Gao, S., (2021). Biochar effects on yield of cereal and legume crops using meta-analysis. Sci. Total Environ., 775: 145869 **(9 pages)**.

Gao, Y.; Shao G.; Yang Z.; Zhang K.; Lu J.; Wang Z.; Wu, S.; Xu, D., (2021). Influences of soil and biochar properties and amount of biochar and fertilizer on the performance of biochar in improving plant photosynthetic rate: A meta-analysis. Eur. J. Agron., 130: 126345 **(23 pages)**.

Ginting, B.; Chiari, W.; Duta, T.F.; Hudaa, S.; Purnama, A.; Harapan, H.; Rizki, D.R.; Puspitah, K.; Idroesa, R.; Meriatna, M.; Iqhrammullah, M., (2023), COVID-19 pandemic sheds a new research spotlight on antiviral potential of essential oils–A bibliometric study. Heliyon. 9(7): e17703 **(18 pages)**.

He, Y.; Yao, Y.; Ji, Y.; Deng, J.; Zhou, G.; Liu, R.; Shao, J.; Zhou, L.; Li, N.; Zhou, X.; Hosseini Bai, S., (2020). Biochar amendment boosts photosynthesis and biomass in C3 but not C4 plants: A global synthesis. GCB Bioenergy. 12(8): 605-617 **(13 pages)**.

Iqhrammullah, M.; Refin, R.Y.; Rasmi, R.I.; Andika, F.F.; Hajjah, H.; Marlina, M.; Ningsih, R., (2023). Cancer in Indonesia: A bibliometric surveillance. Narra X. 1(2): e86 **(10 pages)**.

Latino, M. E.; Menegoli, M.; Corallo, A., (2022). Agriculture digitalization: A global examination based on bibliometric analysis. IEEE Trans. Eng. Manage. 71: 1330-1345 **(16 pages)**.

Li, X.; Wang, T.; Chang, S.X.; Jiang, X.; Song, Y., (2020). Biochar increases soil microbial biomass but has variable effects on microbial diversity: A meta-analysis. Sci. Total Environ. 749: 141593 **(11 pages)**.

Liu, X.; Wang, H.; Liu, C.; Sun, B.; Zheng, J.; Bian, R.; Drosos, M.; Zhang, X.; Li, L.; Pan, G., (2021). Biochar increases maize yield by promoting root growth in the rainfed región. Arch. Agron. Soil Sci., 67(10): 1411-1424 **(14 pages)**.

Liu, Y.; Li, H.; Hu, T.; Mahmoud, A.; Li, J.; Zhu, R.; Jiao, X.; Jing, P., (2022). A quantitative review of the effects of biochar application on rice yield and nitrogen use efficiency in paddy fields: A meta-analysis, Sci. Total Environ., 830: 154792 **(12 pages)**.

Luo, L.; Wang, J.; Lv, J.; Liu, Z.; Sun, T.; Yang, Y.; Zhu, Y.G., (2023). Carbon sequestration strategies in soil using biochar: advances, challenges, and opportunities, Environ. Sci. Technol., 57(31): 11357-11372 **(16 pages)**.

Mühl, D.D.; de Oliveira, L., (2022). A bibliometric and thematic approach to agriculture 4.0, Heliyon. 8(5): e09369 **(13 pages)**.

Neogi, S.; Sharma, V.; Khan, N.; Chaurasia, D.; Ahmad, A.; Chauhan, S.; Singh, A.; You, S.; Pandey, A.; Bhargava, P.C., (2022). Sustainable biochar: A facile strategy for soil and environmental restoration, energy generation, mitigation of global climate change and circular bioeconomy, Chemosphere. 293: 133474 **(14 pages)**.

Pokharel, P.; Ma, Z.; Chang, S.X., (2020). Biochar increases soil microbial biomass with changes in extra-and intracellular enzyme activities: A global meta-analysis, Biochar. 2: 65-79 **(15 pages)**.

Pratama, Y.; Kadir, M.; Rivaldi, A.; Mulya, I.; Amirah, S.; Iqhrammullah, M., (2024). Bibliometric analysis of the impact

of environmental degradation on women and the importance of women's representation, Global J. Environ. Sci. Manage., 10(3): 939-954 **(16 pages)**.

Puspita, K.; Chiari, W.; Abdulmadjid, S.N.; Idroes, R.; Iqhrammullah, M., (2022). Four decades of laccase research for wastewater treatment: insights from bibliometric analysis, Int. J. Environ. Res. Public Health. 20(1): 308 **(16 pages)**.

Rejeb, A.; Abdollahi, A.; Rejeb, K.; Treiblmaier, H., (2022). Drones in agriculture: A review and bibliometric analysis, Comput. Electron. Agric., 198: 107017 **(19 pages)**.

Schmidt, H.P.; Kammann, C.; Hagemann, N.; Leifeld, J.; Bucheli, T.D.; Monedero, M.A.S.; Cayuela, M.L., (2021) Biochar in agriculture–A systematic review of 26 global meta-analyses, GCB Bioenergy. 13(11): 1708-1730 **(23 pages)**.

Shalini, S. S.; Palanivelu, K.; Ramachandran, A.; Raghavan, V., (2021). Biochar from biomass waste as a renewable carbon material for climate change mitigation in reducing greenhouse gas emissions—a review, Biomass Convers. Biorefin. 11(5): 2247-2267 **(21 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)**.

Wang, J.; Wang, B.; Bian, R.; He, W.; Liu, Y.; Shen, G.; Xie, H.; Feng, Y., (2024). Bibliometric analysis of biochar-based organic fertilizers in the past 15 years: Focus on ammonia volatilization and greenhouse gas emissions during composting, Environ. Res., 243: 117853 **(11 pages)**.

Wang, J.; Wang, S., (2019). Preparation, modification and environmental application of biochar: A review. J. Clean. Prod., 227: 1002-1022 **(21 pages)**.

Xie, Y.; Wang, L.; Li, H.; Westholm, L.J.; Carvalho, L.; Thorin, E.; Yu, Z.; Yu, X.; Skreiberg, Ø., (2022). A critical review on production, modification and utilization of biochar. J. Anal. Appl. Pyrol., 161: 105405 **(41 pages)**.

Zhang, B.; Li, W.; Guo, Y.; Zhang, Z.; Shi, W.; Cui, F.; Lens, P.N. L.; Tay, J.H., (2020), Microalgal-bacterial consortia: from interspecies interactions to biotechnological applications, Renew. Sustain. Energy Rev., 118:109563 **(20 pages)**.

Zulkifli, B.; Fakri, F.; Odigie, J.; Nnabuife, L.; Isitua, C. C.; Chiari, W., (2023). Chemometric-empowered spectroscopic techniques in pharmaceutical fields: A bibliometric analysis and updated review, Narra X, 1(1): e80 **(16 pages)**.

AUTHOR (S) BIOSKETCHES

Bakar, B.A., M.Si., Senior Researcher, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *basr004@brin.go.id*
- ORCID: 0000-0001-8275-0646
- Web of Science ResearcherID: NA
- Scopus Author ID: 57215469062
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Idawanni, Ph.D., Senior Researcher, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *idaw001@brin.go.id*
- ORCID: 0000-0002-8466-7421
- Web of Science ResearcherID: NA
- Scopus Author ID: 57215088886
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Azis, A., M.P., Senior Researcher, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *abdu094@brin.go.id*
- ORCID: 0000-0001-9921-7426
- Web of Science ResearcherID: NA
- Scopus Author ID: 55216814700
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Kurniawati, S., M.Si., Junior Researcher, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia .
- Email: *srik007@brin.go.id*
- ORCID: 0000-0002-2101-9611
- Web of Science ResearcherID: NA
- Scopus Author ID: 57200727094
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Giamerti, Y., M.Agr.Sc., Junior Researcher, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *yuti002@brin.go.id*
- ORCID: 0009-0003-6760-5426
- Web of Science ResearcherID: NA
- Scopus Author ID: 57218915230
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

AUTHOR (S) BIOSKETCHES

Yardha, Ir., Principal Investigator, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *yard001@brin.go.id*
- ORCID: 0009-0004-1991-8994
- Web of Science ResearcherID: NA
- Scopus Author ID: 57212874365
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Resmayeti, P., M.Si., Principal Investigator, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *resm002@brin.go.id*
- ORCID: 0000-0003-4378-5410
- Web of Science ResearcherID: NA
- Scopus Author ID: 57222903611
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Abdullah, S., M.S., Principal Investigator, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *syahrial.abd57@gmail.com*
- ORCID: 0009-0002-8284-0494
- Web of Science ResearcherID: NA
- Scopus Author ID: 58073488200
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Jonharnas, Ir., Senior Researcher, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *jonharnas@brin.go.id*
- ORCID: 0000-0001-9333-2140
- Web of Science ResearcherID: NA
- Scopus Author ID: 58524407200
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Mustikawati, D.R., Dra., Principal Investigator, Research Center for Food Crops, National Research and Innovation Agency (BRIN), Cibinong, Bogor (16911), Indonesia.
- Email: *dewi060@brin.go.id*
- ORCID: 0000-0003-2491-5398
- Web of Science ResearcherID: NA
- Scopus Author ID: 57217114768
- Homepage: https://brin.go.id/orpp/pusat-riset-tanaman-pangan/page/personil-sumberdaya-manusia

Chiari, W., S.Mat., Master's Student, Division of Mathematical and Physical Sciences, Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa, Japan.
- Email: *williamschiari@gmail.com*
- ORCID: 0000-0001-8305-2997
- Web of Science ResearcherID: NA
- Scopus Author ID: 57226012762
- Homepage: https://www.nst.kanazawa-u.ac.jp/eng/

Wikurendra, E.A., Ph.D., Associate Lecturer, [1]Department of Health Scieces , Faculty of Humanities and Health Sciences, Curtin University, Miri (98000), Malaysia. [2]Doctoral School of Management and Organizational Sciece, Hungarian University of Agriculture and Life Science, Kaposvar (7400), Hungary.
- Email: *edzaaria@curtin.edu.my*
- ORCID: 0000-0002-5020-375X
- Web of Science ResearcherID: Y-5226-2018
- Scopus Author ID: 57225988981
- Homepage: https://humanities.curtin.edu.my/

HOW TO CITE THIS ARTICLE

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.

DOI: 10.22034/gjesm.2024.10.SI.15

URL: https://www.gjesm.net/article_715793.html

Global J. Environ. Sci. Manage. 10(SI): 251-262, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Radiation hazards from natural radionuclides contained in rice from former tin mining land

J. Mellawati[1,*], N. Madyaningarum[1], E.A. Fajrianshah[1], E.B. Jumpeno[1], T.R.D. Larasati[2], N. Mulyana[2], E. Nurtjahya[3], K. Khotimah[1]

[1] Research Center for Safety, Metrology, and Nuclear Quality Technology, National Research and Innovation Agency, PUSPIPTEK Serpong, South Tangerang, 15314, Indonesia

[2] Research Center of Radiation Processing Technology, National Research and Innovation Agency, PUSPIPTEK Serpong, South Tangerang, 15314, Indonesia

[3] Department of Biology, Universitas Bangka Belitung, Merawang, Bangka Belitung Island, Indonesia

ARTICLE INFO

Article History:
Received 19 March 2024
Revised 23 May 2024
Accepted 29 July 2024

Keywords:
Natural radionuclides
Radiation hazards
Rice
Tin mining

ABSTRACT

BACKGROUND AND OBJECTIVES: Rice (Oryza sativa L) cultivated at former tin mining land has the potential to absorb natural radionuclides from the soil where it grows. Radionuclides found in rice can po-tentially lead to exposure to ionizing radiation, thereby influencing the likelihood of developing. The aim of study is to assess the levels of natural radionuclides in rice, cal-culate the annual effective dose, and evaluate the additional lifetime cancer risk result-ing from radiation exposure via the consumption of rice.
METHODS: Rice sampling was carried out, then 1 kilogram was weighed and sealed in a standard Marinelli container. Placed for approximately 30 days before gamma spectrometer measurements to allow the decay products to reach secular equilibrium. Utilizing a high purity germanium detector, the radioactivity of the samples was quantified through a gamma spectrometer. Data obtained to calculate daily intake of radionu-clides, annual effective dose, and Lifetime Cancer Risk probability.
FINDINGS: Rice sourced from previous tin mining areas in Indonesia has been considered safe for consumption. While radium and uranium were not detected in the rice, elevated levels of Thorium and Potassium were observed, exceeds the reference value. The estimated annual effective dose that people receive by consuming rice is still lower than the an-nual limit for the general public recommendation and the world average. The estimat-ed risk of Indonesian people getting cancer due to rice consumption is 1.23 people per 10,000 population, lower than reference value (2.9 people per 10,000 population). The absence of cancer risk associated with this method indicates that the agricultural land in Bangka Belitung Province remains suitable for rice cultivation. This finding has holds significance within the realm of environmental risk assessment.
CONCLUSION: Rice samples obtained from former tin mining land actually did not contain the natu-ral radionuclides radium and uranium, but radionuclides thorium and potassium were found. The concentrations of radionuclides thorium and potassium exhibited varia-tions in activity levels, surpassing the reference value but remaining below the global average threshold. The annual effective dose is still lower than the average annual in-take dose in the world. The estimated risk of cancer from consuming rice was found to be 1.23 people per 10,000 population or a range of 0.55 to 2.67 people per 10,000 population who are potentially at risk of developing cancerThe lifetime risk of cancer-related death is reported to be lower than the public recommendation, with 2.9 indi-viduals per 10,000 population being affected. Rice consumers from former tin mining areas in Indonesia (Bangka) continue to be classified as safe.

DOI: 10.22034/gjesm.2024.10.SI.16

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

NUMBER OF REFERENCES
41

NUMBER OF FIGURES
1

NUMBER OF TABLES
3

*Corresponding Author:
Email: *june_mellawati@yahoo.co.id*
Phone: +8129 415 563
ORCID: 0000-0002-8610-725X

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Ingestion of natural radionuclides can result in exposure to ionizing radiation, posing a potential health risk due to the harmful effects on the human body. These radionuclides consist of charged particles and high-energy photons (Abu Bakar *et al*., 2019). These natural radionuclides are Uranium-238 (^{238}U), Thorium-232 (^{232}Th) and its derivatives Radium-226 (^{226}Ra), and Thorium-228 (^{228}Th), as well as Potassium-40 (^{40}K). Prolonged exposure to radiation emitted by naturally-occurring radionuclides carries substantial health hazards, such as the risk of developing long-term illnesses and sustaining harm to bodily organs (Moukadiri *et al.,* 2023). Uranium and its radioactive decay products have been identified as having carcinogenic properties, leading to the development of cancer in cases where human exposure surpasses established safety thresholds. Furthermore, these substances pose heightened risks associated with environmental radiation (Chen *et al.,* 2021). Prolonged exposure to uranium and its radioactive derivatives (radium) has been linked to kidney, human lungs, and respiratory system damage, ^{232}Th in lungs, liver, and skeletal tissue, while ^{40}K in muscles (Pinero-García *et al*., 2021). Previous research found transfer factor values for natural radionuclides ^{226}Ra, ^{238}U, ^{232}Th and ^{40}K in several foodstuffs (Nurtjahya *et al*., 2023). Fish, vegetables, fruit and tubers from tin mining areas contain natural radionuclides ^{226}Ra, ^{232}Th and ^{40}K (Syarbaini *et al*., 2014). Natural radionuclides ^{226}Ra, ^{232}Th, and ^{40}K were also found in foodstuffs from tin mining land in Nigeria (Muhammad *et al*, 2024). The data presented indicates the presence of natural radionuclide contamination in various food items sourced from tin mining areas. Rice serves as the primary grain in Indonesia's daily staple food diet. As a staple food for the Asian population, including Indonesia, the average consumption of rice in Indonesia is 0.222 kilogram (kg) per day per person (Central Statistics Agency, 2024). The natural radionuclides ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th, and ^{40}K are found in almost all food commodities including rice, but there will be concerns if rice plants are cultivated on former tin mining land. The government is actively expanding rice cultivation in different parts of Indonesia to address the essential requirements of the Indonesian populace and to serve as a significant revenue stream for indigenous farmers. The Bangka Belitung Province as the largest tin producer in Indonesia is one of the government's targets for rice self-sufficiency. Based on these reasons, research was conducted to determine the concentration of natural radionuclides ^{238}U, ^{232}Th and ^{40}K in rice products from former tin mining land. The assessment of radiological risks involves the calculation of daily intake of radionuclides and the annual effective dose experienced by individuals, along with the estimation of excess lifetime cancer risk (ELCR) in order to evaluate the potential long-term carcinogenic effects of consuming rice. Previous research conducted a health study on rice from the market, obtaining ^{226}Ra and ^{40}K (Muthmainah *et al*., 2020). Research on rice from former tin mining land has never been conducted in Indonesia. The primary objective of this study is to investigate the safety of rice consumption and assess the appropriateness of utilizing previously tin-mined areas for agricultural purposes. The hypothesis of this study is to determine the correlation between agricultural products from former tin mining land and cancer risk. The study seeks to assess the presence of natural radionuclides in rice, calculate the annual effective dose, and evaluate the additional lifetime risk of cancer resulting from radiation exposure through the consumption of rice. The aim of study is to assess the levels of natural radionuclides in rice, calculate the annual effective dose, and evaluate the additional lifetime cancer risk resulting from radiation exposure via the consumption of rice. The study area for this study is located between 02° 15' 0.0" south latitude to 106°00.0.00' east latitude, namely Bangka Belitung Province, Indonesia, which is known as the largest tin mining area in Indonesia. Rice was sampled in 2022-2023 from several areas, including Matras Village, Payung Village, Serdang Village, and Jelutung Village.

MATERIALS AND METHODS

Sample collection and preparation

The white rice samples (eight) and brown rice samples (three) were obtained from rice cultivation sites in Bangka Belitung Province, Indonesia, as illustrated in Fig. 1. Approximately 5 kg of each sample was placed in polyethylene plastic bags, labeled, and transferred to the laboratory (IAEA, 1989). The sample was subjected to drying at a temperature of 110 degrees Celsius (°C) in order to eliminate moisture content and achieve a consistent weight. Subsequently, it was finely ground using a grinder and sifted through 40 mesh sieves. Weighed ± 1 kg of dried sample and sealed in a standard Marinelli container



Fig. 1: Geographic location of the study area and sampling from Bangka Belitung Province, Indonesia

(volume 1 liter (L), stored for about 30 days before gamma spectrometer measurements to allow the decay products to reach secular equilibrium, following guidelines (IAEA, 1989; Olivares *et al.,* 2018).

Radionuclide measurement

The sample's radionuclides were quantified utilizing a gamma spectrometer equipped with a high-purity Germanium detector (HP Ge), coaxial p-type, and a relative efficiency of 60 percent (%). The energy calibration used 1.95 kiloelectron volt (keV) resolution (FWHM) for a peak of Cobalt-60 (^{60}Co) 1332 keV and Cesium-137 (^{137}Cs) for 24 hours. The radionuclide ^{238}U was measured as Protactinium-234 (^{234}Pa) at gamma energies of 1001 keV, ^{226}Ra was measured as Bismuth-214 (^{214}Bi) and Lead-214 (^{214}Pb) at gamma energies of 609.31 keV to 351.92 keV. Thorium-232 is measured as ^{228}Ac at 911.07 and 968.97 keV, while ^{228}Th is measured as ^{212}Pb and Talium-208 (^{208}Tl) at 238.63 keV and 583.2 keV, while ^{40}K is determined directly at energies of 1460.75 keV (Jibiri *et al*., 2007). The assessment of uncertainty entailed the examination of variables including statistical counting, ambient noise, and systematic inaccuracies that may impact the outcome (Mellawati *et al*., 2021). The uncertainty number displayed in the activity concentration table.

The activity concentration of radionuclide in the sample (concentration: C, Bacquerel per year (Bq/kg)

The activity concentration of radionuclides (Mellawati *et al*., 2021) in rice samples was calculated using the efficiency formula using Eq. 1 (Jibiri *et al*., 2007), and the uncertainty of the measurement (Mellawati *et al*., 2021) and calculated using Eq. 2 (Jibiri *et al*., 2007):

$$C = \frac{(Ns-Nb)}{(\varepsilon_\gamma \cdot p\gamma \cdot W)} \pm \sigma \quad (1)$$

$$\sigma = \sqrt{\frac{\sum(Xi-\bar{X})^2}{n}} \quad (2)$$

In this equation, *C* is the activity concentration of radionuclide in the sample (Bq/kg) N_S represents the gamma count rate (/s) of the sample, N_b is the background gamma count rate (/s), ε_γ is the efficiency of the HP Ge detector for a specific g-ray, p_γ the probability of gamma-ray emission, and W is the sample mass kilogram (kg), while is the uncertainty of the measurement.

Where, X_i represents the *i* data value, $\bar{x}$ is the average of data values, and n is the total number

of data points. For determining the minimum detectable concentration (MDC) with a 95 % confidence level, using Eq. 3 (Mellawati *et al*., 2021):

$$MDC = 4.66 \frac{\sqrt{\frac{N_b}{t^2_b}}}{\varepsilon_\gamma \cdot p_\gamma \cdot W \cdot C_f} \quad (3)$$

MDC is the minimum detectable concentration (Bq/kg), N_b is the background gamma count rate (/s), t_b is the background counting time (seconds), ε_γ is the efficiency of the HP Ge detector for a specific γ-ray, p_γ is the probability of gamma-ray emission, W is the sample mass kilogram (kg), and C_f is the self-absorption correction factor. The MDC measurement data for radionuclides ^{226}Ra, ^{238}U, ^{232}Th, ^{228}Th, and ^{40}K are 0.16; 0.26; 0.13; 0.25; and 1.35 Bq/kg.

Radiological health risk assessment (Daily radionuclide intake, estimation of effective dose due to ingestion, estimation of excess lifetime cancer risk)

The radionuclide's activity concentration is utilized in the computation of the daily intake that is deposited in the human body on a daily basis. The value is utilized in the computation of the annual effective dose in order to quantify the dose received for the purpose of implementing radiation protection protocols, as it signifies the risk associated with the effects of radiation exposure. Daily intake of radionuclides is considered to be the accumulation of ^{226}Ra, ^{238}U, ^{232}Th, ^{228}Th, and ^{40}K into the human body due to consumption of rice grown in former tin mining areas. Data on the average rice consumption level for Indonesians (per capita consumption per year) was 81.02 kg/year (Central Statistics Agency, 2024). The information provided allows for the estimation and calculation of the daily intake of radionuclides from consuming rice, as outlined in Eq. 4 (Jayasinghe *et al*. 2020; ICRP, 1996):

$$D_{in} = \frac{Ci \times Cing}{Yd} \quad (4)$$

Where, D_{in} is the individual's daily radionuclide intake (Bq/kg), C_i is the activity concentration of radionuclide (Bq/kg), C_{ing} is the per capita consumption per year, Y_d is the number of days consumed per year (365 days).

Radionuclide intake through ingestion is well described by the ICRP Human Gastrointestinal Tract Model (Jayasinghe *et al*. 2020; ICRP, 1996; Harb, 2015). The annual effective ingested dose can be calculated by multiplying the radioactivity of each radionuclide ingested per year by the dose conversion coefficient (Adedokun *et al*., 2019). The cumulative intake of radiation is calculated by adding together the individual doses of each radionuclide. Based on data on the activity concentrations of ^{232}Th, ^{228}Th and ^{40}K radionuclides detected in rice samples, as well as the amount of rice consumed per year, and the dose conversion factor for each specific radionuclide, an estimate of the annual effective dose received by the Indonesian people through rice consumption can be calculated. The annual effective dose estimation is derived from the methodology suggested by the United Nation Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (Saeed, 2011) using Eq. 5 (Adedokun *et al*., 2019):

$$AED = C \times R \times F_C \quad (5)$$

AED is the annual effective dose (Sv/y), C is the specific activity of radionuclides (Bq/kg), R is the annual rice consumption level (kg/y), for the average rice consumption of the Indonesian population is estimated at 81.02 kilogram per year(kg/y) (Central Statistics Agency, 2024) , F_C is the dose conversion factor for adult consumption (≥ 17 years) for the specific radionuclide ^{232}Th is 0.23×10^{-6} milisieverts per Becquerel (mSv/Bq), ^{228}Th is $0.7X10^{-7}$ mSv/Bq, and ^{40}K is 6.2×10^{-9} mSv/Bq. The calculation formula to obtain the estimated annual effective dose (ICRP, 1996), using Eq. 4 (Jayasinghe *et al*. 2020). The ELCR metric serves as a tool for assessing the possible carcinogenic impacts of extended ingestion of food items that contain radionuclides. As per the guidelines set by the ICRP, the risk coefficient for lethal cancer resulting from low levels of radiation exposure is 0.05 per Sievert (/Sv) (ICRP, 1996). The ELCR is calculated using an equation according to United nation UNSCEAR recommendations (UNSCEAR, 2000). The assessment of prolonged radiological risks in this investigation encompasses the mean lifespan or life expectancy (age) of the Indonesian population, with women having an average of 72.18 years and men having an average of men 70.17 years. The ELCR value data is intended to assess the potential for radiation exposure in the community and the possible biological impacts of such exposure due to rice consumption (UNSCEAR, 2000). ELCR is determined using Eq. 6 (UNSCEAR, 2000):

Table 1: The activity concentration (Bq.kg^{-1}) of ^{226}Ra, ^{238}U, ^{232}Th, ^{228}Th, and ^{40}K in Rice Samples

Sample Code	^{226}Ra	^{238}U	^{232}Th	^{228}Th	^{40}K
WR-1	< MDC	< MDC	0.26 ± 0.14	1.97 ± 0.20	42.80 ± 1.86
WR-2	< MDC	< MDC	0.39 ± 0.10	0.91 ± 0.11	40.21 ± 1.62
WR-3	< MDC	< MDC	< MDC	< MDC	25.69 ± 1.34
WR-4	< MDC	< MDC	0.19 ± 0.05	0.33 ± 0.13	54.82 ± 2.26
WR-5	< MDC	< MDC	0.58 ± 0.18	0.30 ± 0.06	66.64 ± 2.51
WR-6	< MDC	< MDC	0.37 ± 0.15	0.40 ± 0.08	30.43 ± 1.31
WR-7	< MDC	< MDC	0.57 ± 0.19	0.68 ± 0.28	30.20 ± 2.13
WR-8	< MDC	< MDC	1.91 ± 0.47	0.99 ± 1.41	61.64 ± 4.05
BR-1	< MDC	< MDC	0.23 ± 0.12	0.26 ± 0.03	40.61 ± 1.60
BR-2	< MDC	< MDC	0.16 ± 0.10	< MDC	48.46 ± 1.94
BR-3	< MDC	< MDC	< MDC	< MDC	44.45 ± 1.40
Min	< 0.16	< 0.26	< 0.13	< 0.25	25.69
Max	-	-	1.91	1.97	66.64
Average:	-	-	0.41	0.53	44.18
Range:	< MDC	< MDC	< 0.13–1.91	< 0.25–1.97	25.69–66.64
(UNSCEAR, 2000) (2000)	0.08	0.02	0.003	0.003	-

Note: WR is white rice, BR is brown rice

$$ELCR = AED \times DL \times RF \quad (6)$$

ELCR is Excess lifetime cancer risk, AED is the annual effective dose due to ingestion Sievert per year (Sv/y), DL is the average of life duration or the lifetime expectancy of Indonesian people is 74.18 for females, and 70.17 for males (Central Statistics Agency, 2024).

RESULTS AND DISCUSSION

Activity concentration of radionuclides

The activity concentrations of radionuclides in the white and brown rice samples are shown in Table 1.

The analysis results of eleven rice samples planted on former tin mining land in different villages showed that natural radionuclides ^{226}Ra and ^{238}U were not detected in either white or brown rice or their activity concentration was lower than the MDC as shown in Table 1. Radionuclides ^{232}Th and ^{228}Th were detected in almost all rice samples analyzed. Thorium and descendants have the potential to cause harm to the kidneys, liver, and lungs within the human body. After three days of exposure to thorium and thoron, physiological alterations in the lung, liver, and kidney are observed (Chaudhury *et al*., 2022). Statisticaly, concentrations of radionuclides varied, ^{40}K 25.69 to 66.64 Bq/kg, ^{232}Th <0.13 to 1.91 Bq/kg and ^{228}Th, <0.26 to 1.97 Bq/kg. Based on Internation Atomic Energy Agency (IAEA) guidelines (2016), the activity concentration has exceeded the reference value recommended by UNSCEAR (UNSCEAR, 2000). The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in rice samples in this study were compared with the same conditions (tin mines) in Nigeria, showing that the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in the rice samples were higher, 7.02; 8.18; and 123.98 Bq/kg (Muhammad *et al*, 2024). In a similar study, rice planted on land 20-50 km from tin mines in Nigeria also contained higher levels of ^{226}Ra, ^{232}Th, and ^{40}K, with each activity 28.01; 44.19; and 35.76 Bq/kg (Abdullahi *et al*, 2018). The fluctuation in radionuclide levels as indicated in Table 1 may be attributed to geological influences (Li *et al.*, 2024). The composition of the soil (Paiva *et al*., 2019) and underlying rocks formation can influence radionuclide concentrations (Kamunda *et al*., 2016). Certain mineral and geological formations may contain higher levels of radioctive elements like ^{232}Th, ^{228}Th ^{226}Ra and ^{238}U, which can affect soil (Li *et al.*, 2024) and subsequently crop uptake (Mellawati and Nurtjahya, 2023). Monitoring this concentration variation is crucial. Tracking changes over an extended period allows for the assessment of the effectiveness of actions taken on previously mined tin land. Epidemiological studies and biomonitoring offer valuable insights into the cumulative impacts of radiation exposure on human health, highlighting the significance of these implications in understanding the effects on the population (Syaiful Anwar and Yuniarti, 2022).

In general, ^{226}Ra, ^{232}Th, ^{40}K are found in rice and their values vary greatly. According to the literature, researchers from several countries in the world have reported that the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K each range between 1.08 to 109.26; 0.70 to 71.97; and 24.05 to 691.71 Bq/kg, even though the rice sample did not come from a former tin mining area (Table

Table 2: The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (Bq/kg) in Rice samples investigated in the presence study compared with those reported in the literature

Origin	^{226}Ra	^{232}Th	^{40}K	Sources
Malaysia (Penang)	1.42	1.03	72.15	Alsaffar *et al*., 2015
Saudi Arabia	1,23	0.70	154.83	Al-Hassan *et al*., 2014
Italy	2.90	2.80	119.30	Desideri *et al*., 2014
India	3.07	34.30	120.80	Shanti *et al*. 2009
India	86.75	53.73	331.24	Najam *et al*., 2015
Ghana	4.72	4.33	104.36	Awudu *et al*. 2012
Saudi Arabia	1.08	1.19	83.08	Al-Zahrani, 2016
Iran	1.55	2.19	110.56	Pourimani and Anoosheh, 2015
Taiwan	0.62	-	24.05	Huang *et al*. 2023
Pakistan	1.50	1.00	195.80	Al-Hassan *et al.*, 2014
Thailand	80.20	40.70	500.76	Najam *et al*., 2015
Iraq	51.15	71.97	691.71	Najam *et al*., 2015
Turkey	80.82	43.31	483.22	Najam *et al*., 2015
USA	109.26	13.67	231.87	Najam *et al*., 2015
Pakistan	73.45	32.56	502.71	Najam *et al*., 2015
Uruguay	107.21	17.85	305.91	Najam *et al*., 2015
Indonesia (Padang)	1.12	< 0.26	28.44	Muthmainah *et al*., 2020
Indonesia (Bangka)	< 0.16	0.41	44.18	Present study

2). The findings of this study indicate that the levels of natural radionuclides in the rice samples analyzed remain within acceptable limits. The study conducted by researchers hailing from India revealed that rice samples sourced from Thailand, Iraq, Turkey, the United States of America (USA), Pakistan, and Uruguay exhibited significantly elevated concentrations of ^{226}Ra (51.15 to 109.26 Bq/kg). Likewise, the radionuclide ^{232}Th ranges from 13.67 to 71.97 Bq/kg, and ^{40}K ranges from 231.87 to 691.71 Bq/kg (Najam *et al*., 2015). Rice samples from former tin mining land in Indonesia (Bangka) only contained relatively low radionuclides ^{232}Th, ^{228}Th, and ^{40}K, although they exceeded the reference levels recommended by UNSCEAR. Almost everyone who researched the radionuclide content in rice found that the activity concentration of ^{40}K radionuclides in rice tended to be higher than that of ^{226}Ra, ^{232}Th, and ^{228}Th, as shown in Table 2. The elevated concentration of ^{40}K in comparison to other radionuclides can be attributed to its prevalence in the soil and the widespread application of Nitrogen Phosphate Potassium (NPK) fertilizer during rice cultivation (Solehah and Samat, 2017). The hierarchy of radionuclide activity concentrations in rice generally follows the order: of ^{40}K > ^{232}Th > ^{238}U (Ugbede *et al*., 2021). These findings indicate that rice plants cultivated on former mining land have the potential to accumulate natural radionuclides, a similar phenomenon also observed in Indonesia (Bangka Belitung Province). Compared to rice from non-former mining land does not contain the radionuclide ^{232}Th, only ^{226}Ra. The absence of any previous mining activity suggests that the land in question does not pose any potential radiological health hazards. The activity concentration of ^{232}Th 1.12 Bq/kg and ^{40}K 28.44 Bq/kg (Muthmainnah *et al*., 2020), lower than research results. However, in all these cases, the concentrations recorded were within the safe limits set by the IAEA (UNSCEAR, 2000).

Daily radionuclide intake (Bq/day)

The accumulation of ^{232}Th, ^{228}Th, and ^{40}K in the human body through the daily intake of radionuclides from rice consumption is detailed in Table 3.

Data on the average level of rice consumption in Indonesia is 81.02 kilogram per year (kg/y) or 222 gram per day (g/d), and in this case, consumption of rice causes a daily intake averages ^{232}Th, ^{228}Th, and ^{40}K, on as much as 0.09; 0.12; and 9.81 Bq/day. The intake of radionuclides ^{232}Th and ^{228}Th was found to be at a maximum of 0.43 and 0.44 Bq/day, respectively. It is worth noting that ^{40}K contributed the highest daily intake among the radionuclides measured, at 5.70–14.79 Bq/day. Plants, including rice, have a significant requirement for potassium as an essential macronutrient, leading to the abundant presence of ^{40}K. (Islam *et al*., 2014). The use of NPK fertilizer during farming activities is also the cause of an increase in ^{40}K radionuclides in crop yields (rice), especially if farmers use high doses (Jibiri *et al*., 2007). This is due to the abun-

Table 3: The average daily intake (Bq/day), the annual effective dose (x10^{-6}), and ELCR value

Sample	Average daily intake (Bq/day)			Average annual effective dose (x10^{-6} mSv/y)				Excess lifetime Cancer Risk (x10^{-6})			
Code	^{232}Th	^{228}Th	^{40}K	^{232}Th	^{228}Th	^{40}K	Total	^{232}Th	^{228}Th	^{40}K	Total
WR-1	0.06	0.44	9.50	4.81	11.16	21.50	37.47	0.1735	0.4028	0.7759	135.23
WR-2	0.09	0.20	8.93	7.33	5,14	20.20	32.67	0.2647	0.1854	0.7289	117.91
WR-3	N	0.07	5.70	N	1.85	12.91	14.76	N	6.6912	0.4658	53.27
WR-4	0.04	0.10	12.17	3.54	2.47	27.54	33.54	0.1279	8.8991	0.9938	121.06
WR-5	0.13	0.07	6.76	1.0.89	1.70	15.28	27.87	0.3931	0.6122	0.5516	100.59
WR-6	0.08	0.09	14.79	6,85	2.25	33.47	42.58	0.2472	0.8129	0.0121	153.66
WR-7	0.42	0.22	13.69	35.65	5.61	30.96	72.23	0.0129	0.2026	0.0118	260.67
WR-8	0.13	0.15	6.70	10.69	3.86	15.17	29.72	0.3858	0.1392	0.5475	107.24
BR-1	0.04	N	10.76	2.97	N	24.34	27.31	0.1072	N	0.8785	98.57
BR-2	0.05	0.06	9.02	4.32	1.49	20.40	26.20	0.1557	5.3611	0.7361	94.55
BR-3	N	N	9.87	N	N	22.33	22.33	N	N	0.8058	80.58

Note: N=none

dance of ^{40}K radionuclides in nature, and the importance of this element in the growth of rice plants. The gamma dose levels (Table 3) resulting from the ingestion of radionuclides ^{232}Th, ^{228}Th, and ^{40}K in the rice samples analyzed varied between 0.0136 and 0.0722 microsievert per year (µSv/year), with an average of 0.03 µSv/year. It is important to note that these doses solely account for the impact of rice consumption and do not consider other variables like cooking methods or the inclusion of food additives like spices and salt. This value is lower than the world average (0.29 mSv/y) (UNSCEAR 2000) and the limit for the public (1 mSv/y) (ICRP 1996). In addition, the value is also smaller than that reported by Bangladesh: 64.23 µSv/y (Nahar *et al*., 2018), Iran: 20.50 to 68.40 µSv/y (Pourimani and Anoosheh, 2015), Nigeria: 38.60 µSv/y (Muhammad *et al*., 2024), and Saudi Arabia: 0.22 µSv/y (Al-Zahrani, 2016). Therefore, it is also important to calculate the risk of cancer (ELCR).

The excess lifetime cancer risk (ELCR)

The ELCR due to consumption of rice containing radionuclides is shown in Table 3. The estimated risk for the population in Indonesia in the range is 0.55 to 2.67 people or 1.23 people (mean) per ten thousand population lower than the UNSCEAR recommended value of 0.29 x 10^{-3} (Najam *et al.*, 2015; UNSCEAR, 2000). This value is smaller than that reported in Nigeria 1.34 (Abdullahi *et al*, 2018) and 4.5 people per ten thousand population (Muhammad *et al*., 2024). The evaluation of cancer risk associated with radiation hazards in the current study aligns with findings from nations with tin mining activities. Another illustration can be seen in the cultivation of vegetables in Peninsular Malaysia. Vegetables do not pose a significant radiological risk to individuals, even in the presence of elevated levels of radionuclides in the soil. The soil samples analyzed in this study exhibit external hazard indices below one, indicating their suitability for agricultural purposes (Solehah and Samat, 2017). The implications for public health in former tin mining areas are the nutritional conditions, which are caused by landscape changes and pollution (Efrizal, 2020). This information is not in line with research results which prove that former tin mining land is still suitable for agricultural use. Policy makers are faced with the challenge of enhancing the utilization of land in areas previously used for tin mining. It is imperative to enhance the nutritional status by carefully choosing agricultural products that are well-suited for cultivation on former mining sites (Efrizal, 2020). The local and central governments are paying more attention to reclamation, since it has been proven that former tin mining land can be used for rice farming. Policies aimed at public health and agricultural productivity may provide further research opportunities (Syaiful Anwar and Yuniarti, 2022). The study indicates a possibility of increasing agricultural operations in previous mining regions; however, it is essential to exercise caution regarding environmental and public health issues, particularly in locations with a background of mining activities. Mining of mineral ore is regarded one of the anthropogenic ways of increasing the activity-concentrations of natural radionuclide in the environment, which pose hazards if the accumulate in crops and are consumed by humans (Abdullahi *et al*, 2018).

CONCLUSION

The research results showed that rice samples obtained from former tin mining land did not contain the natural radionuclides ^{226}Ra and ^{238}U, but only contained the natural radionuclides ^{232}Th, ^{228}Th and ^{40}K. The activity concentrations of radionuclides ^{232}Th, ^{228}Th, and ^{40}K are quite variable with range between < 0.13 to 1.91 Bq/kg (average: 0.47 Bq/kg), < 0.25 to 1.97 Bq/kg (average: 0.57 Bq/kg), and 25.69 to 66.64 Bq/kg (average: 44.18 Bq/kg). This amount has exceeded the reference values set by UNSCEAR *viz,* ^{232}Th and ^{228}Th of 0.03 Bq/kg respectively. Although it is still lower than the average reported by several countries in the world, *viz*, ^{232}Th is 20.04 Bq/kg while ^{40}K is 237.22 Bq/kg. The collective mean daily consumption of radionuclides ^{232}Th, ^{228}Th, and ^{40}K from consuming rice varied between 5.78 to 14.96 Bq/d, with an average. The daily intake of radionuclides comes from ^{232}Th as much as 0.09 Bq/d, ^{228}Th 0.13 Bq/d, and ^{40}K 9.81 Bq/d. In facts that ^{40}K radionuclide is the largest contributor to daily intake of radionuclides. The average of total annual effective dose received by rice consumers shows a range between 0.15 to 0.72 x 10^{-3} µSv/y, or the average is 0.33x10^{-3} µSv. This effective dose comes from the daily intake of radionuclide ^{232}Th of 0.29 x 10^{-3} µSv, ^{228}Th 0.12 x 10^{-3} µSv, and ^{40}K 0.82 x 10^{-3} µSv. Nevertheless, this quantity remains below the global average annual effective dose of 0.29 mSv/y and the public limit set by ICRP recommendations of 1 mSv/y. Estimates of the lifetime risk of cancer in residents who consume rice from former tin mining areas show that as many as 1.23 people or ranging from 0.55 to 2.67 people per ten thousand population have a potential risk of developing cancer. The findings of this study indicate that the lifetime probability of cancer-related mortality is below the permissible threshold, specifically at 2.9 individuals per ten thousand members of the population. Based on the data presented, the conclusion drawn is that consuming rice grown on former tin mining land in Indonesia (Bangka Belitung Province) is considered safe. The study indicates that the land remains suitable for rice cultivation with no major safety issues. This discovery paves the way for the potential expansion of agricultural practices into regions once designated for mining purposes. The implication of these findings is that local and central governments could potentially reconsider regulations concerning the management of former mining land. The implementation of regulations and policy that prioritize public health, give a chance to facilitate ongoing research. The study focused on improving the caliber of agricultural goods cultivated on land that has been mined. Overall, the research points toward a positive outlook regarding the safety and usability of former tin mining land for agriculture, providing basis for policy review and potential expansion of agriculture activities in such areas.

AUTHOR CONTRIBUTIONS

J. Mellawati performed the conceptualization, methodology, supervision, project administration, writing, original draft preparation. N. Madyaningarum performed the writing, review, editing. E. A. Fajrianshah performed the visualization, formal analysis. E.B. Jumpeno helped in the methodology, review, editing. T.R.D. Larasati helped in sampling, formal analysis. N. Mulyana performed the formal analysis. E. Nurtjahya performed the project administration, investigation, resources. K. Khotimah helped in writing, review, editing, formal analysis.

ACKNOWLEDGEMENT

The authors would like to thank the Ministry of Education and Culture, Research and Technology of the Republic of Indonesia for supporting funding and facilitating this research through grant programs [No.105/E4.1/AK.04.PT/2021 and 185.B/UN50/L/PP/2021]. The author also expresses his dee-pest gratitude to the Center for Research and Community Service, University of Bangka Belitung, the Research Center for Metrology Safety, and Nuclear Quality Technology, the National Research and Innovation Agency (BRIN), Puspiptek Serpong, South Tangerang regarding this joint project

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

©2024 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International Li-

cense, 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
^{228}Ac	Actinium-228
AED	Annual effective dose
^{214}Bi	Bismuth-214
Bq/day	Becquerel per day
Bq/kg	Becquerel per kilogram
C	Activity concentration
^{o}C	Degree Celsius
C_f	The self-absorption correction factor
C_i	The activity concentration of radionuclide
C_{ing}	The per capita consumption per year
^{60}Co	Cobalt-60
D_{in}	The individual's daily radionuclide intake
DL	Duration of life
ELCR	Excess lifetime cancer risk
F_c	Dose conversion factor for adult consumption
g/y	Gram per year
g/d	Gram per day
IAEA	International Atomic Energy Agency
ICRP	The International Commission on Radiological Protection
^{40}K	Kalium-40
Kg	Kilogram
Kg/y	Kilogram per year
keV	Kiloelectron volt
L	Liter
MDC	Minimum detectable concentration
mSv/y	Millisieverts per year
NPK	Nitrogen phosphate potassium
N_s	Represents the gamma count rate
N_b	The background gamma count rate
^{234}Pa	Protactinium-234
^{214}Pb	Lead-214
^{212}Pb	Lead-218
p_γ	The probability of gamma-ray emission
R	Annual rice consumption level
^{226}Ra	Radium-226
RF	Risk Factor
/S	Per seconds
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USA	United State of America
/Sv	Per sieverts
Sv/y	Sievert per year
^{232}Th	Thorium-232
^{228}Th	Thorium-228
^{208}Tl	Talium-208
tb	Background counting time
^{238}U	Uranium-238

W	The sample mass
Y_d	Number of days consumed per year
$\mu Sv/y$	Microsieverts per year
ε_γ	The efficiency of the HP Ge detector

REFERENCES

Abdullahi, M.A.; Alhassan, S.; Obajemu, O., (2018). Measurement of radiological hazard indices in cereals grown around Ririwai Tin Mine, Kano State, North Western Nigeria. J. Agric. Crops. 11: 141–146 **(6 pages).**

Abu Bakar, Nurul Fathihah.; Amira Othman, Siti.; Amirah Nor Azman, Nor Farah; Saqinah Jasrin, Nurin., (2019). Effect of ionizing radiation towards human health: A review. IOP Conference series: Earth Environ. Sci., 268(1): 1-6 **(6 pages).**

Adedokun, M.B.; Aweda, M.A.; Maleka, P.P.; Obed, R.I.; Ogungbemi, K.I.; Ibitoye, Z.A., (2019). Natural radioactivity contents in commonly consumed leafy vegetables cultivated through surface water irrigation in Lagos state, Nigeria. J. Radiat. Res. Appl. Sci., 12(1): 147–156 **(10 pages).**

Al-Hassan, A.A.; Abdel-Salam, A.M.; El-Taher, A., (2014). Assessment of natural radioactivity levels and heavy metals in different types of rice consumed in Qassim, Saudi Arabia. J. Life Sci., 11(11): 829–836 **(8 pages).**

Alsaffar, M.S.; Jaafar, M.S.; Kabir, N.A.; Ahmad, N., (2015). Distribution of ^{226}Ra, ^{232}Th, and ^{40}K in rice plant components and physico-chemical effects of soil on their transportation to grains. J. Radiat. Res. Appl. Sci., 8(3): 300–310 **(11 pages).**

Al-Zahrani, J.H., (2016). Natural Radioactivity and Heavy Metals Measurement in Rice and Flour Consumed by the Inhabitants in Saudi Arabia. Adv. J. Food Sci. Technol., 12(12): 698–704 **(7 pages).**

Awudu, A.R.; Faanu, A.; Darko, E.O.; Emi-Reynolds, G.; Adukpo, O.K.; Kpeglo, D.O.; Otoo, F.; Lawluvi, H.; Kpodzro, R.; Ali, I.D.; Obeng, M.K.; Agyeman, B., (2012). Preliminary studies on ^{226}Ra, ^{228}Ra, ^{228}Th and ^{40}K concentrations in foodstuffs consumed by inhabitants of Accra metropolitan area, Ghana. J. Radioanal. Nucl. Chem., 291(3): 635–641 **(7 pages).**

Central Statistics Agency, (2024). Life expectancy rates (indonesians) according to province and gender, 2022-2023. BPS.

Central Statistics Agency, (2024). Weekly average consumption of several food items commodity per capita, 2007-2023. Indonesian Central Statistics Agency. BPS.

Chaudhury, D.; Sen, U.; Sahoo, B. K.; Bhat, N.N.; Kumara K.S.; Karunakara, N.; Biswas, S.; Shenoy P.S.; Bose, B., (2022). Thorium promotes lung, liver and kidney damage in BALB/c mouse via alterations in anti-oxidant systems. Chem. Biol. Interact., 363: 1-16 **(16 pages).**

Chen, L.; Liu, J.; Zhang, W.; Zhou, J.; Luo, D.; Li, Z., (2021). Uranium (U) source, speciation, uptake, toxicity and bioremediation strategies in soil-plant system: A review. J. Hazard. Mater., 413: 1-21 **(21 pages).**

Desideri, D.; Meli, M.A.; Roselli, C.; Forini, N.; Rongoni, A.; Feduzi, L., (2014). Natural radionuclides in Italian diet and their annual intake. J. Radioanal. Nucl. Chem., 299(3): 1461–1467 **(7 pages).**

Efrizal, W. (2020). Dampak Ekologis Bangka Belitung terhadap Keadaan Gizi dan Kesehatan. Jurnal Ilmu Gizi Indonesia. 1(2): 1–9 **(9 pages).**

Harb, S., (2015). Natural radioactivity concentration and annual effective dose in selected vegetables and fruits. J. Phys. G: Nucl. Part. Phys., 2015(3): 70–73 **(4 pages).**

Huang, W.-H.; Liu, Y.-Y.; Lin, S.-C.; Yeh, Y.-L.; Chen, T.-C., (2023). Assessment of doses from ingestion of naturally occurring radionuclides k-40 and ra-226 in rice consumed in taiwan. Radiat. Prot. Dosim., 199(4): 312–317 **(6 pages).**

IAEA, (1989). Measurement of radionuclides in food and the environment. A guidebook. Int. J. Environ. Radioact., 11(2).

ICRP, (1996). Age-dependent doses to members of the public from intake of radionuclides: part 5 compilations of in-gestion and inhalation dose coefficients (International Commission on Radiological Protection, Ed.; ICRP Publication 72). Pergamon Press Oxford.

Islam, M.S.; Mohanta, M.K.; Saha, A.K.; Mondol, A.; Hoque, M.M.; Roy, A.K., (2014). Carbofuran-Induced Alterations in Body Morphometrics and Histopathology of Liver and Kidneys in the Swiss Albino Mice Mus Musculus L. Int. J. Sci. Res. Environ. Sci., 2(9): 308–322 **(15 pages).**

Jayasinghe, C.; Pinnawala, U.C.; Rathnayaka, T.; Waduge, V., (2020). Annual committed effective dosage from natural radionuclides by ingestion of local food growing in mineral mining area, Sri Lanka. Environ. Geochem. Health. 42(7): 2205–2214 **(10 pages).**

Jibiri, N.N.; Farai, I.P.; Alausa, S.K., (2007). Estimation of annual effective dose due to natural radioactive elements in ingestion of foodstuffs in tin mining area of Jos-Plateau, Nigeria. J. Environ. Radioact., 94(1): 31–40 **(10 pages).**

Kamunda, C.; Mathuthu, M.; Madhuku, M. (2016). An assessment of radiological hazards from gold mine tailings in the province of Gauteng in South Africa. Int. J. Environ. Res. Public Health. 13(1): 1-10 **(10 pages).**

Li, H.; Wang, Q.; Zhang, C.; Su, W.; Ma, Y.; Zhong, Q.; Xiao, E.; Xia, F.; Zheng, G.; Xiao, T., (2024). Geo-chemical Distribution and Environmental Risks of Radionuclides in Soils and Sediments Runoff of a Uranium Mining Area in South China. Toxics. 12(1):1-16 **(16 pages).**

Mellawati, J.; Nurtjahya, E. (2024). Natural radionuclide content in horticulture plants from former tin mining land and health risk assessment: A case study on Bangka Belitung Island, Indonesia. IOP Conference Series: Earth Environ. Sci., 1297(1): 1-10 **(10 pages)**.

Mellawati, J.; Suhariyono, G.; Wahyudi, Wiyono, M., (2021). Concentration of NORM (238U, 232Th and their decay products) and Cs-137 in air particulate at around the NPP site candidate in West Kalimantan. AIP Conference Proceeding. 020039 **(9 pages).**

Moukadiri, H.; Noukrati, H.; Ben Youcef, H.; Iraola, I.; Trabadelo, V.; Oukarroum, A.; Malka, G.; Barroug, A., (2023). Impact and toxicity of heavy metals on human health and latest trends

in removal process from aquatic media. Int. J. Environ. Sci. Technol., Springer Berlin Heidelberg, 3407-3444 **(38 pages).**

Muhammad, Abdu Nasiru; Ismail, A.F.; Garba, N.N., (2024). Natural radioactivity in food crops and soil and estimation of the concomitant dose from tin mining areas in Nigeria. J. Taibah Univ. Sci., 18(1): 1-11 **(11 pages).**

Muthmainnah, M.; Milvita, D.; Wiyono, M., (2020). Penentuan Konsentrasi Radionuklida (Ra-226, Th-232, K-40, dan Cs-137) pada Bahan Pangan Menggunakan Spektrometer Gamma di Pasar Raya Kota Padang. J. Fisika Unand., 9(3): 394–400 (**7 pages).**

Nurtjahya, E.; Mellawati, J.; Pratama, D.; Syahrir, S., (2023). Study of soil–to–plant transfer factors (TFs) of 226Ra, 232Th, and 40K on plants cultivated on ex–tin mining land in Bangka Belitung, Indonesia. J. Environ. Radioact., (Issue 107144), 261: 1-6 **(6 pages).**

Nahar, A.; Asaduzzaman, K.; Islam, M.M.; Rahman, Md.M.; Begum, M., (2018). Assessment of natural radio-activity in rice and their associated population dose estimation. Radiat. Eff. Defects Solids. 173(11–12): 1105–1114 (**10 pages).**

Najam, L.A.; Tawfiq, N.F.; Kitha, F.H., (2015). Measuring radioactivity level in various types of rice using NaI (Tl) detector. Am. J. Eng. Res., 3: 126–132 (**7 pages).**

Olivares, D.M.M.; Koch, E.S.; Guevara, M.V.M.; Velasco, F.G., (2018). Determination of uranium and thorium using gamma spectrometry: a pilot study. Conference Series: J. Phys., 975: 1-6 **(6 pages).**

Paiva, I.; Marques, R.; Santos, M.; Reis, M.; Prudêncio, M. I.; Waerenborgh, J.C.; Dias, M.I.; Russo, D.; Car-doso, G.; Vieira, B.J.C.; Carvalho, E.; Rosa, C.; Lobarinhas, D.; Diamantino, C.; Pinto, R., (2019). Naturally occurring radioactive material and risk assessment of tailings of polymetallic and Ra/U mines from legacy sites. Chemosphere. 223: 171–179 (**9 pages).**

Piñero-García, F.; Thomas, R.; Mantero, J.; Forssell-Aronsson, E.; Isaksson, M., (2021). Radiological impact of naturally occurring radionuclides in bottled water. Food Control. 130: 108302: 1-9 **(9 pages).**

Pourimani, R.; Anoosheh, F., (2015). A study on transfer factors of environmental radionuclides: Radionuclide transfer from soil to different varieties of rice in gorgan, Iran. Iranian J. Med. Phys., 12(3): 189–199 **(11 pages).**

Saeed, M.A., (2011). Measuring radioactivity level in various types of rice using hyper pure germanium (HPGe) detector. Int. J. Phys. Sci., 6(32): 7335-7340 **(6 pages).**

Shanthi, G.; Maniyan, C. G.; Allan, G.; Raj, G.; Thampi, J.; Kumaran, T., (2009). Radioactivity in food crops from high-background radiation area in southwest India. Curr. Sc., 9 (97): 1331-1335 **(5 pages).**

Solehah, A.R.; Samat, S.B., (2018). Radiological impact from natural radionuclide activity concentrations in soil and vegetables at former tin mining area and non-mining area in Peninsular Malaysia. J. Radioanal. Nucl. Chem., 315(2): 127–136 **(10 pages).**

Syaiful Anwar, M.; Yuniarti, S. (2022). Kebijakan Pengelolaan Lingkungan Pasca Tambang di Wilayah Pesisir Kepulauan Bangka Belitung Berbasis Good Governance. Seminar Nasional Penelitian dan Pengabdian Pada Masyarakat. 2022: 36–40 (**5 pages).**

Syarbaini; Warsona, A.; Iskandar, D. (2014). Natural Radioactivity in Some Food Crops from Bangka-Belitung Islands, Indonesia, Atom Indonesia. 40(1): 27-32 **(6 pages).**

Ugbede, F.O.; Osahon, O.D.; Agbalagba, E.O. (2021). Radiological risk assessment of 238U, 232Th and 40K in soil and their uptake by rice cultivated in CAS paddy environment of Abakaliki, Nigeria. Chem. Afr., 4(3): 691–701 **(11 pages).**

UNSCEAR, (2000). Sources and effects of ionizing radiation - UNSCEAR 2000 Report to the General Assembly, with Sci. Ann.,1(4979). United Nations Publication.

AUTHOR (S) BIOSKETCHES

Mellawati, J., Ph.D., Professor, Research Center for Safety, Metrology, and Nuclear Quality Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia .
- Email: *june001@brin.go.id*
- ORCID: 0000-0002-8610-725X
- Web of Science ResearcherID:NA
- Scopus Author ID: 15739690800
- Homepage: https://intra.brin.go.id/home/profile_sivitas/june001

Madyaningarum, N., M.D., Research Center for Safety, Metrology, and Nuclear Quality Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia
- Email: nuni005@brin.go.id
- ORCID: 0009-0007-2495-334X
- Web of Science ResearcherID: NA
- Scopus Author ID:57216547668
- Homepage: https://simpeg.brin.go.id/admin/kepegawaian/pegawai/profilen

Fajrianshah, E.A., M.D., Research Center for Safety, Metrology, and Nuclear Quality Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email:*evan005@brin.go.id*
- ORCID: 0000-0002-7615-4503
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://intra.brin.go.id/home/profile_sivitas/evan005

AUTHOR (S) BIOSKETCHES

Larasati, T.R.D., M.D., Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: trir001@brin.go.id
- ORCID: 0000-0002-9198-1523
- Web of Science ResearcherID: NA
- Scopus Author ID: 57217128588
- Homepage: https://intra.brin.go.id/home/profile_sivitas/trir001

Jumpeno, E.B., M.D., Research Center for Safety, Metrology, and Nuclear Quality Technology, National Research and Innovation Agency, PUSPIPTEK Serpong, South Tangerang, 15314, Indonesia.
- Email: *bene001@brin.go.id*
- ORCID: 0009-0006-7907-0993
- Web of Science ResearcherID: NA
- Scopus Author ID: 57222553470
- Homepage: https://intra.brin.go.id/home/profile_sivitas/bene001

Nurtjahya, E., Associate Professor, department of Biology, Bangka Belitung University, Pangkal Pinang, Indonesia.
- Email: *eddy_nurtjahya@yahoo.go.id*
- ORCID: 0000-0003-4641-069X
- Web of Science ResearcherID: NA
- Scopus Author ID: 35105782200
- Homepage: https://biologi.ubb.ac.id/pengajar.html

Mulyana, N., M.D., Research Center of Radiation Processing Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: *nana012@brin.go.id*
- ORCID: 0009-0009-5191-8181
- Web of Science ResearcherID: NA
- Scopus Author ID: 57201470918
- Homepage: https://intra.brin.go.id/home/profile_sivitas/nana012

Khusnul, K., M.D., Research Center for Safety, Metrology, and Nuclear Quality Technology, National Research and Innovation Agency, Puspiptek Serpong, South Tangerang, 15314, Indonesia.
- Email: khus003@brin.go.id
- ORCID: 0009-0002-2872-8573
- Web of Science ResearcherID: NA
- Scopus Author ID:58080084400
- Homepage: https://intra.brin.go.id/home/profile_sivitas/khus003

HOW TO CITE THIS ARTICLE

Mellawati, J.; Madyaningarum, N.; Fajrianshah, E.A.; Jumpeno, E.B.; Larasati, T.R.D.; Mulyana, N.; Nurtjahya, E.; khusnul, K., (2023). Radiation hazards from natural radionuclides contained in rice from former tin mining land. Global J. Environ. Sci. Manage., 10(SI): 251-262.

DOI: 10.22034/gjesm.2024.10.SI.16

URL: https://www.gjesm.net/article_714681.html

Global J. Environ. Sci. Manage. 10(SI): 263-278, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Utilization of agricultural waste to reduce enteric methane emissions on livestock in tropical environment

Sulistyo[1], Pranoto[2,*], E. Mahajoeno[3], S.H. Pranolo[4], A. Sofyan[5], H. Herdian[5], B. Haryanto[6], R.H. Praptana[7]

[1] *Postgraduate School, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia*

[2] *Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia*

[3] *Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia*

[4] *Study Program of Chemical Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia*

[5] *Research Center for Animal Husbandry, National Research and Innovation Agency, Cibinong, Bogor, Indonesia*

[6] *Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Serpong, Tangerang Selatan, Indonesia*

[7] *Research Center for Food Crops, National Research and Innovation Agency, Cibinong, Bogor, Indonesia*

ARTICLE INFO

Article History:
Received 29 April 2024
Revised 03 June 2024
Accepted 05 August 2024

Keywords:
Agricultural waste
Enteric fermentation
Feed quality
Greenhouse gases emissions
Livestock management

ABSTRACT

BACKGROUND AND OBJECTIVES: The livestock sector contributes to increasing greenhouse gas emissions. Livestock emissions primarily stem from enteric fermentation, a process heavily impacted by the quality of the animals' feed. The utilization of fermented rice straw as a source of crude fiber for animal feed is one solution for providing high-quality feed. Central Java plays a significant role in the cattle farming and rice production sectors within Indonesia Indonesia. The purpose of this study was to determine the contribution of greenhouse gas emissions resulting from fermented straw feed formula commonly practiced by cattle farmers in Central Java.

METHODS: In vitro experiments were carried out to measure greenhouse gas production, utilizing three different formulas that were arranged in a completely randomized design with six replications. The three feed formula treatments were: 30 percent king grass + 35 percent rice bran+ 35 percent wheat bran (treatment one), 30 percent fermented rice straw + 35 percent rice bran + 35 percent wheat bran (treatment two), and 30 percent fermented rice straw + 70 percent concentrate (treatment three). The analysis of nutrient composition and enteric gas emissions was conducted to evaluate the quality of the feed formulation, as well as to assess both feed digestibility and the production of greenhouse gases throughout the digestive process. The gas production was measured at regular intervals of 8, 16, 24, 36, and 48 hours. The methane, nitrous oxide, and carbon dioxide contents were analyzed using gas chromatography. The nutrient content and digestibility of dry matter and organic matter were examined through analysis of variance, while the estimated greenhouse gas emissions were determined utilizing the ideal gas equation approach.

FINDINGS: The quality of the feed formula influences the amountof greenhouse gases emission produced by enteric fermentation processes. The quality of the feed in treatment one was comparable to that observed in treatment two. The treatment three feed formulation had a crude protein content approximately 3 percent higher than that of treatment one and treatment two. There were no significant variations observed in the digestibility of dry matter and organic matter values across the different treatments. The feed formula treatment two can reduce potential greenhouse gas emissions by 1.81 percent from treatment one, whereas treatment three can reduce potential greenhouse gas emissions by 27.78 percent from treatment one and by 26.4 percent from treatment two. These results indicate that feed formulas with higher crude protein content have greater potential to reduce greenhouse gas emissions. This result provides a basis for implementing strategies aimed at enhancing feed quality by making use of agricultural waste, as part of a broader effort to manage livestock with lower greenhouse gas emissions.

CONCLUSION: Utilization of fermented straw has the potential to reduce greenhouse gas emissions resulting from enteric fermentation and contamination of unutilized straw waste and has the opportunity to reduce land use and greenhouse gas emissions from forage plants. It is imperative to enhance the quality of feed in order to effectively utilize fermented straw as a feed with low greenhouse gas emissions. It is essential to conduct more extensive studies on the variations in feed formulations that arise from regional resource disparities, the economic viability of incorporating fermented straw with diverse feed components, and the life cycle assessment of straw utilization as a feed ingredient based on geographical, social, economic, technological, and environmental dimensions.

DOI: 10.22034/gjesm.2024.10.SI.17

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

NUMBER OF REFERENCES
70

NUMBER OF FIGURES
4

NUMBER OF TABLES
3

*Corresponding Author:
Email: *pakpranoto@gmail.com*
Phone: +62 812-2581-006
ORCID: 0000-0002-1626-1147

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Climate change and global warming are mostly caused by greenhouse gas emissions (GHG) (Hashima et al., 2022). Livestock husbandry is responsible for the emission of two greenhouse gases, namely methane (CH4) and nitrous oxide (N2O). Increased GHG emissions are undoubtedly a result of Indonesia's initiative to increase the number of livestock to meet animal protein needs. It is estimated that ruminant animals are responsible for approximately 95 percent (%) of the total methane (CH4) emissions worldwide, contributing to 18% of the overall greenhouse gas (GHG) emissions present in the atmosphere (Noor *et al.,* 2014). Beef cattle account for the majority of the livestock sector's CH_4 emissions, contributing 41% of the total. Dairy cattle, pigs, buffaloes, poultry, and small ruminants follow with 9%, 20%, 9%, and 8% of the emissions, (Gerber *et al.,* 2013). The primary source of greenhouse gas emissions, specifically methane (CH4), produced by cattle arises from the fermentation of feed that has been decomposed by rumen bacteria (Swarnam *et al.,* 2024). Enteric fermentation accounts for 39.1% of CH_4 emissions, while manure management accounts for 4.3% (Rojas *et al.,* 2017). Cattle produce approximately 73% of the CH_4 produced during digestion, whereas sheep and buffalo produce 10% apiece, and goats produce 4%. Approximately 80–95% of this gas is produced in the rumen and 5–20% is produced in the large intestine (Noor *et al.,* 2014). Between 7 to 12 percent of the energy utilized by ruminant animals is emitted as methane gas, originating from the rumen (Johnson and Johnson, 1995). Anaerobic fermentation of carbohydrates is performed by CH_4 gas-producing bacteria called methanogens. The global warming potential of the generated CH_4 gas is 25 times greater than that of carbon dioxide (CO_2) (Aprilliza *et al*., 2021). The quality of feed significantly influences the quantity of methane (CH4) gas generated through enteric fermentation in ruminant animals. The production of elevated levels of CH4 gas during rumen fermentation may be attributed to the consumption of a low-quality diet. High fiber content, por digestibility of organic matter (OM) (<38.5%), and extended rumen retention time are indicative of low-quality feed (Boadi *et al.,* 2002; McAllister and Newbold, 2008). Ruminants require crude fiber as an essential component of their diet to facilitate proper digestion. Fullfiling calorie and protein requirements, crude fiber promotes improved feed intake, intestinal bacteria, and overall gut health. For ruminant animals, the quality of crude fiber is essential as a source of nutrition (Singh *et al.,* 2022; Zhu *et al.,* 2022). Protein is a crucial factor that impacts the growth of microbes in the rumen. In regions such as the tropics and subtropics, the bovine diet tends to have lower levels of protein compared to other regions (Castro-Montoya and Dickhoefer, 2020). Because of its high fiber content, forage in the tropics generates more CH_4 gas (Kennedy and Charmley, 2012). The emission of enteric CH4 is becoming a significant issue, as it possesses a greater potential for release compared to atmospheric CO2 and accounts for 39% of the overall emissions originating from the agricultural sector (Gerber *et al.,* 2013). The CH_4 produced by intestinal fermentation poses both obstacles and potential for developing GHG emission reduction and mitigation measures (Kamyab *et al.,* 2024). The growing focus on climate change from scientists, governmental bodies, and consumers has placed significant pressure on the livestock sector to mitigate greenhouse gas emissions. Effective livestock management plays a crucial role in influencing these emissions. When GHG emissions in the atmosphere are reduced, more sunshine will reach photovoltaic panels, increasing renewable energy generation prospects (Naderipour *et al.,* 2020). Australia has a significantly larger cattle population compared to Japan, resulting in higher nitrogen emissions attributed to variations in feed quality (Dhia *et al.,* 2015). Increasing livestock productivity helps reduce GHG emissions because increased productivity can produce more products per emission (Menezes *et al.,* 2016; Prima *et al.,* 2019). Continuous endeavors are necessary to enhance the quality of pastures and optimize feed nutrition in order to decrease gas emissions produced during enteric fermentation in ruminant animals (Mahmud and Prima, 2021). Fermented rice straw can replace forage feed because it has a high crude protein content that is comparable to that of king grass (Sulistyo *et al.,* 2019). Rice straw production worldwide annually ranges from 800-1,000 million tons, with Asia alone contributing 600-800 million tons (IRRI, 2024). However, the optimization of rice straw management has not been achieved, leading to significant challenges for both the environment (Sakhiya *et al.,* 2023). As an easy and affordable method of tillage, many farmers burn

their straw on the field. When rice straw is burned, toxic air pollutants such as carbon monoxide (CO), volatile organic compounds (VOCs), and particle matter (PM) are released (Sakhiya *et al.*, 2023). Rice straw is commonly utilized as a direct application to the soil, resulting in insufficient soil fertilization due to its rapid decomposition (IRRI, 2024). The anaerobic breakdown of agricultural wastes and straw during prolonged floods is responsible for over 65% of the world's CO_2 emissions (Allen *et al.,* 2020). Central Java is one of Indonesia's cattle development and rice production centers, contributing to the country's meat and rice needs. In 2022, Central Java had a dairy and beef cattle population of 2,054.33 heads, with a rice harvest area of 1.70 million hectares (BPS, 2024). As part of an attempt to manage low GHG emission livestock in Central Java, the potential for using rice straw for animal feed is extremely high. Initiatives aimed at sustainable management of agricultural waste should incorporate the utilization of fermented straw as animal feed. This approach not only seeks to enhance the value of agricultural by-products but also aims to mitigate negative environmental impacts. (Kamyab *et al.,* 2024). The potential GHG emissions generated by feed formulas containing fermented forage and straw can be determined by in vitro testing of enteric fermentation processes, as well as efforts to reduce potential GHG emissions and enhance the quality of various feed formulae used by farmers. The hypothesis of the study posits that the feed formula incorporating fermented straw exhibits superior quality and produces lower levels of greenhouse gas emissions compared to the feed formula incorporating forage. This study is unique in that it includes data on GHG emissions from three feed formulations utilized by farmers. . The findings of this study can serve as valuable resources for shaping policies related to the management of low-GHG emission cattle production, and can also be used as a foundation for further in-depth studies that aim to advance initiatives promoting eco-friendly and sustainable livestock practices. The aim of the current study is to estimate the reductions of GHG emissions by using fermented straw in cattle feed formulas. This study has been carried out in Central Java Province, Indonesia in 2022.

MATERIALS AND METHODS

Research design

The in vitro study was conducted from February to December 2022. The study used a one-way completely randomized design (CRD) with three treatments, and each treatment was repeated six times. The treatments consisted of feed formulas commonly fed by cattle farmers in Central Java, Indonesia, namely, 30% king grass + 35% rice bran + 35% wheat bran (T1), 30% fermented rice straw + 35% rice bran + 35% wheat bran (T2), and 30% fermented rice straw + 70% concentrate (T3). The study used a one-way completely randomized design (CRD) with three treatments, and each treatment was repeated six times. Cattle producers in Central Java frequently use king grass forage and rice straw as cattle fodder (Suwignyo *et al.,* 2016). Agricultural wastes such as soybean groats, bran, palm meal, coffee husk, and molasses are frequently used as concentrate components to promote cattle growth (Riyanto *et al.,* 2020). The nutrient composition and enteric gas emissions were examined to assess the feed formulation's quality and to evaluate feed digestibility and greenhouse gas production during the digestion process. Feed nutrient content analysis was conducted at the Nutrition and Food Science Laboratory, Faculty of Animal Science, Sebelas Maret University, Surakarta, Indonesia. Production of GHG was carried out in vitro at the National Research and Innovation Agency (Badan Riset dan Inovasi) (BRIN) Laboratory in Gunungkidul, Yogyakarta, Indonesia.

Research procedures

The in vitro research process requires three main components: feed samples, rumen fluid, and McDougall's solution (buffer). McDougall buffer is a pH-stabilizing buffer chemical that is often used in in vitro studies to determine ruminant feed digestibility (Camacho *et al.,* 2019). A total of 0.20 gram (g) of feed sample was gathered from each replicate following the sieving of the cattle feed using a 1 mm sieve. The rumen fluid was extracted from the digestive waste of cattle at the slaughterhouse in Gunungkidul, Yogyakarta. Rumen fluid was obtained by squeezing the digestive remains from the rumen

filtered using four layers of cheesecloth. he rumen fluid was deposited into a thermos that had been warmed to a temperature of 39-40 degrees Celsius (°C) by utilizing hot water. The rumen fluid is filtered again using four layers of cheesecloth to ensure that no solid residue remains. The CO_2 gas gas underwent a 30-minute process of passing through the liquid in order to establish an anaerobic setting. The temperature of the rumen fluid was maintained at 39-40°C while waiting for the buffer solution to be prepared. McDougall's solution was prepared through the combination of buffer solution, macro and micro mineral solution, resazurin solution, and reduction solution. Macro mineral solution was made by dissolving sodium hydrogen carbonate ($NaHCO_3$; 84,007 g/mol), potassium hydrogen phosphate (K_2HPO_4; 174,2 g/mol), and magnesium sulfate ($MgSO_4$; 120,366 g/mol) in 1 liter of distilled water. A solution of micro minerals was prepared by dissolving calcium chlorid 2-hydrate ($CaCl_2{\cdot}2H_2O$; 147.01 g/mol), manganese (II) chloride tetrahydrate ($MnCl_2.4H_2O$; 197.90 g/mol), cobalt (II) chloride hexahydrate ($CoCl_2.6H_2O$; 237.90 g/mol), and ferric chloride hexahydrate ($FeCl_3.6H_2O$; 270.33 g/mol) in 100 ml of distilled water. A buffer solution was prepared by dissolving sodium bicarbonate ($NaHCO_3$) and 4 grams of ammonium hydrogen carbonate ($(NH_4)HCO_3$) with a molar mass of 79.06 g/mol in one liter of distilled water. Resazurin solution was made by dissolving 100 mg of resazurin ($C_{12}H_6NNaO_4$; 80%) in 100 mL of distilled water. Reduction solution was made by combining sodium hydroxide (NaOH: 40 g/mol) and sodium sulfide pentahydrate ($Na_2S.5H_2O$; 248.18 g/mol) in distilled water (47.5 ml). he chemical compounds employed in the study were produced by Merck KGaA, located in Darmstadt, Germany. The solution underwent stirring and heating procedures until a noticeable alteration in color occurred, transitioning color from purple to pink. The CO_2 gas is added to maintain an anaerobic environment. McDougall's solution is added to the rumen fluid, followed by the addition of CO_2 gas. The feed sample is inserted into a syringe that has been lined with paper in order to avoid adherence to the inner walls of the syringe. The syringe is equipped with a hose, a clamp, and a seal designed to prevent the leakage of samples. The fed sample syringe was combined with rumen fluid and McDougall's solution in a water heater, and the mixture was left to incubate for 48 hours at 39°C, which is the same temperature as a cow's rumen. This procedure was done in accordance with Tilley and Terry's (1963) method, which was adjusted for the duration of fermentation.

Data collection

The nutritional composition of the feed analyzed included neutral detergent fiber (NDF) and acid detergent fiber (ADF) acquired through the method of Van Soest *et al.,* (1991), as well as crude protein (CP), extract ether (EE), and ash obtained from the proximate testGas was generated in vitro by pushing gas through the wall of a syringe containing a fermented feed sample solution. An anaerobic atmosphere was maintained for fifteen minutes using CO2 gas. A vaseline-coated piston was placed inside the syringe to aid in compression. rior to sealing the syringe, all air bubbles were permitted to ascend to the surface in order to prevent any air from becoming trapped. The syringe was incubated in a water bath at 39°C for 48 hours. After 48 hours, gas production will normalize (Sofyan *et al.,* 2017). Periodically, measurements of gas production were made at 8, 16, 24, 36, and 48 hours. The gas contents of CH_4, N_2O and CO_2 were analyzed using gas chromatography (GC) at the Greenhouse Gas Laboratory, Indonesian Agricultural Environment Instrument Standard Testing Institute (IAESTI), Pati, Central Java, Indonesia. The dry matter and organic matter of the feed were weighed both before and after the invitro test in order to assess the digestibility of dry matter (DMD) and OMD. The values for DMD and OMD were calculated using the Eqs. 1 and 2 (Hristov *et al.* 2019):

$$\text{DMD} = \frac{\text{Weight of dry matter before in vitro test} - \text{Weight of dry matter after in vitro test}}{\text{Weight of dry matter before in vitro test}} x100 \quad (1)$$

$$\text{OMD} = \frac{\text{Weight of organic matter before in vitro test} - \text{Weight of organic matter after in vitro test}}{\text{Weight of organic matter before in vitro test}} x100\% \quad (2)$$

Data analysis

The R Studio software (version 4.1.0) was employed to conduct an analysis of variance, focusing on the

Table 1: Feed nutrients content of feed formula treatments T1, T2, and T3.

Nutrients (%)	T1	T2	T3	p<0.05
CP	9,51±0,62[b]	9,34±0,54[b]	12,59±0,71[a]	0,001**
EE	2,08±0,05[a]	1,92±0,95[a]	0,95±0,08[a]	0,088
Ash	14,92±0,87[a]	16,54±0,44[a]	15,92±0,64[a]	0,065
NDF	70,17±2,91[a]	67,05±7,33[a]	58,78±7,1[a]	0,141
ADF	47,63±1,58[a]	47,39±3,6[a]	46,03±1,00[a]	0,682
TDN	57.98	61.16	62.38	

Note: Significant differences are shown by superscript letters behind numbers in the same row; ** = significant different

data pertaining to the nutrient composition of the feed, along with DMD and OMD. Duncan Multiple Range Test (DMRT) was performed if significant differences were identified between treatments. The feed formula quality of each treatment was assessed in relation to Kearl's (1982) formula for total digestible nutrients (TDN) and protein requirements in cattle.. The ideal gas equation method was used to compute the expected volume of GHG emissions (CH_4, N_20, and CO_2).

RESULTS AND DISCUSSION

Feed nutrient content

The results indicated that there was no notable variance in the nutritional composition of the feed provided in treatments T1 and T2. The CP content of the T3 treatment differed significantly from that of the T1 and T2 treatments (p<0.05). In comparison to feed formulas T1 and T2, the levels of EE, NDF, and ADF were reduced in feed formula T3. Table 1 provides detailed information about feed nutrients content. Feed formulations with higher CP content will have lower NDF and ADF levels (Pazla *et al.*, 2023).

According to the formula proposed by Kearl (1982), the feed formulations designed for the three treatments satisfied the standard protein needs of pregnant female cows during both the initial and final trimesters of their gestation. Bulls weighing 150, 200, 250, and 300 kilogram (kg) can only acquire the basic minimum of nutrition from the feed formulations of treatments T1 and T2, resulting in limited protein satisfaction for bulls. Bulls weighing 350 kg are able to ingest adequate protein from feed formulations T1 and T2 in order to fulfill their body weight gain needs of less than 0.5 kg/head/d. While the T3 treatment feed formulation stimulates body weight gain of more than 0.75 kg/head/day in bulls weighing 200-350 kg, it can also meet the protein requirements of bulls of different body weights. The digestibility of protein is influenced by both the protein content present in the feed and the quantity of protein that reaches the digestive system. The digestibility of crude protein is influenced by the protein content present in the ration. Rations containing low levels of protein exhibit reduced digestibility, while those with higher protein content demonstrate the opposite effect (Tillman *et al.*, 2005). Microbial proteins can contribute up to 80% of the protein needs in ruminant animals. Protein in ruminant feed contains rumen degradable protein (RDP) and rumen undegradable protein (RUP). Rumen microorganisms utilize rumen degradable protein as a substrate for the synthesis of microbial proteins (Salami *et al.*, 2020). Protein in diverse feed items is required to supply both RDP and RUP. Roughage is a significant food source for ruminants and has an impact on the rumen microbiota, which is vital for growth and digesting. The T1 treatment feed formula incorporates king grass as a fiber source, while the T2 and T3 treatment feed formulas contain fermented straw. The process of fermenting feed components prior to their consumption by ruminants enhances both digestibility and the nutritional value of the feed, while also allowing for the utilization of feed materials that would otherwise be unsuitable for feeding. Silage feeding can enhance beef cattle growth and rumen fermentation performance by altering the rumen microbiota and regulating amino acid, carbohydrate, and nucleotide metabolisms (Cui *et al.*, 2022). Animal

forage nutrition modeling relies heavily on estimating feed energy from the total digestible nutrients (TDN) of the forage. The TDN standards play a crucial role in formulating ruminant feed by providing a measure of the energy content present in the feed (Woli *et al.,* 2020). Based on the Kearl's (1982) formula, all feed formula treatments contain the standard TDN content for mother cows. The T1 treatment can only achieve the TDN criterion for body weight gain of 0.5 kg/head/d in bulls weighing 150, 200, and 250 kg, and 0.75 kg/head/d in bulls weighing 300 to 350 kg. The T2 and T3 treatment feed formulations are capable of fulfilling the TDN feed requirements necessary for achieving a maximum body weight gain of 0.75 kg per head per day in bulls weighing between 150-350 kg. Beef cattle can meet their energy requirements with high-quality forage and fiber, but additional energy sources are required to sustain productivity. he feed formulations for T2 and T3 treatments meet the TDN requirements needed to achieve a daily body weight gain of 0.75 kg per bull in the specified weight range (Tomar *et al.,* 2022).

Total gas production

The total gas production for all three treatments revealed that, in comparison to T2 and T3, the feed formula used in the T1 treatment treatment had a lower protein level and produced more gas overall (Fig. 1). The amount of feed and energy ingested by ruminants plays a crucial role in determining the rate of gas emissions resulting from enteric fermentation (IPCC, 2007). Feeds deficient in some nutrients or with low protein content might create gas, which can lead to poor digestion and symptoms like crude fiber or low energy. Because of its greater NDF concentration and lower energy content, the T1 treatment feed formula produced more gas. Forage feeds contain the structural carbohydrate known as NDF. An elevation in NDF intake leading to prolonged retention times in the rumen can potentially lead to improved fermentation and heightened gas production (Gaviria-Uribe *et al.,* 2020). High NDF diets have the potential to alter the rumen microbial population, which would enhance methanogenesis and boost gas production (Zhao *et al.,* 2023). Elevated gas production may arise due to heightened rumen activity resulting from high intake of NDF (Goopy *et al.,* 2020).

Production of CH_4, N_2O and CO_2

Various gases, microbial proteins, and volatile fatty

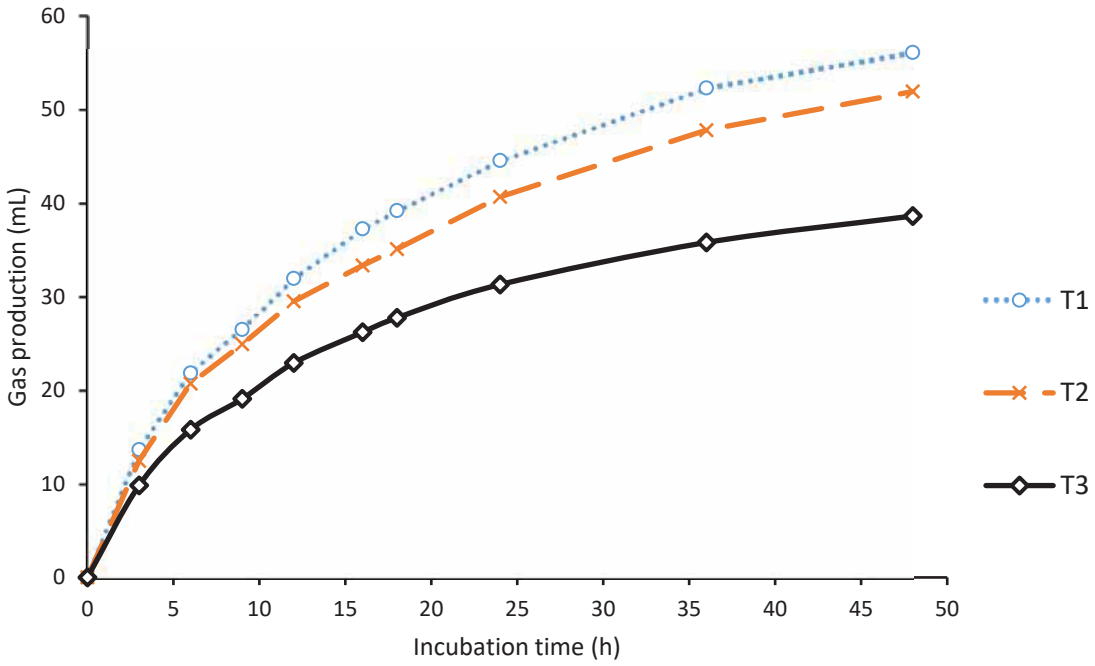


Fig. 1: Total gas production from in vitro test results of feed formula treatments T1, T2 and T3.

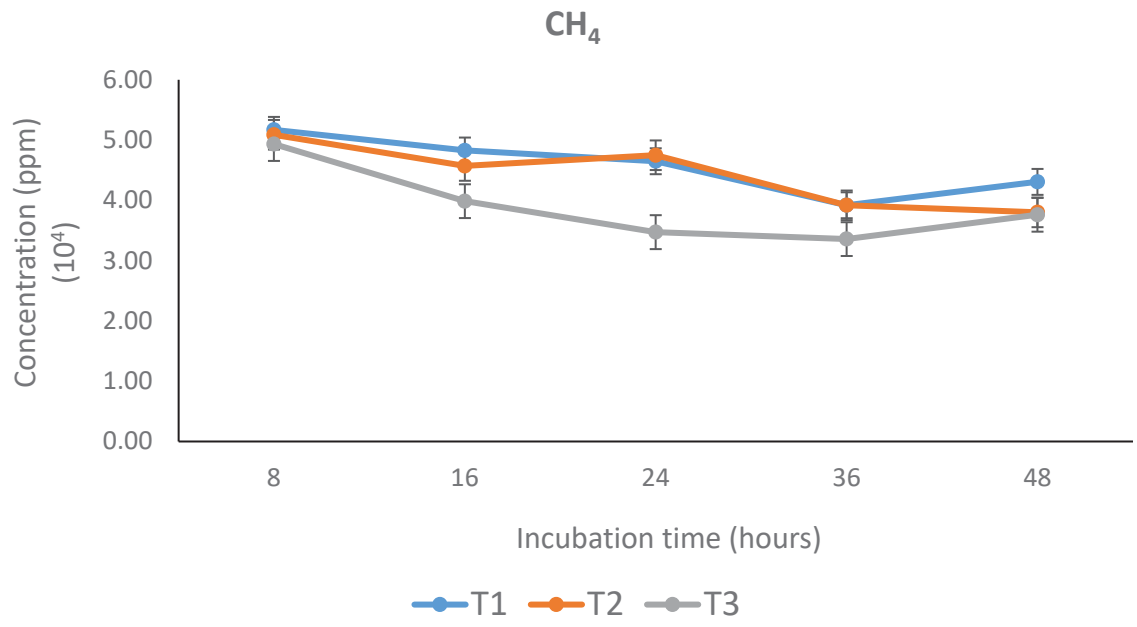


Fig. 2: Production of CH_4 from the in vitro test of feed formula treatments T1, T2 and T3

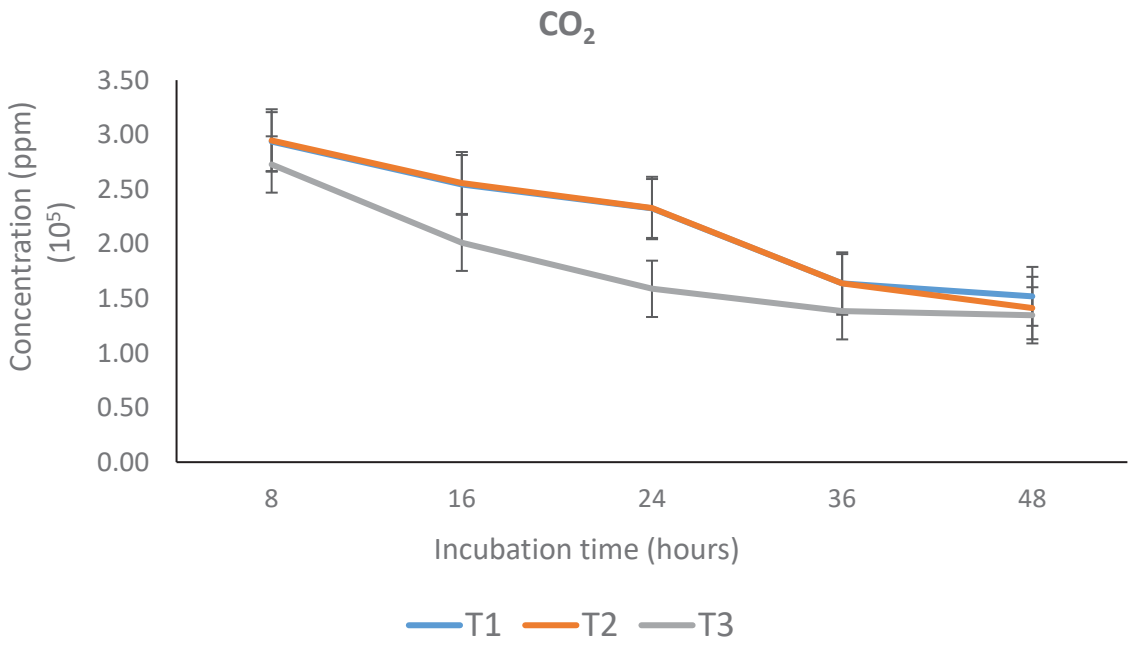


Fig. 3: Production of CO_2 from the in vitro test of feed formula treatments T1, T2 and T3

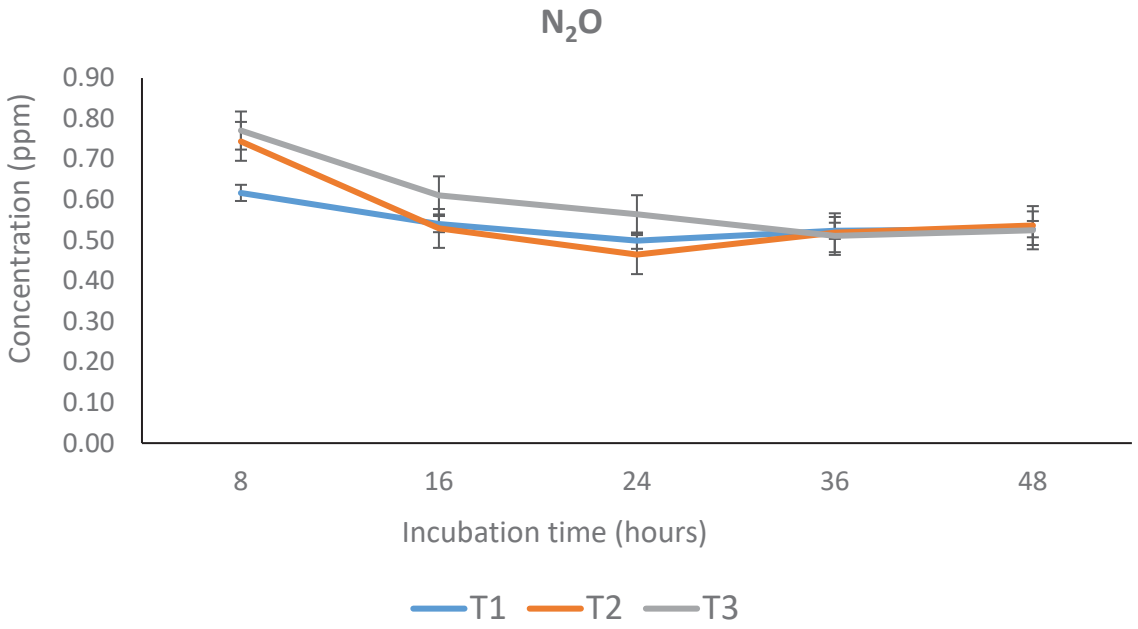


Fig. 4: Production of N_2O from the in vitro test of feed formula treatments T1, T2 and T3.

acids (VFA) are generated during the fermentation of grain by anaerobic rumen bacteria. The amount of breakdown and metabolic energy content of feed for ruminants can be ascertained by measuring the volume of gas generated during fermentation (Dhakal *et al.,* 2023). Figs. 2, 3 and 4 illustrate the volume of CH_4, N_2O and CO_2 gases at each hour of observation during the incubation process of the three feed formula treatments that represent the resulting GHG emissions. The three feed formula treatments generated gas in a pattern that was generally similar for CH_4, N_2O, and CO_2. The CH_4 and CO_2 emissions from feed formula treatment T3 were less than those from treatments T1 and T2. The inclusion of a feed mixture consisting of 40% fermented rice straw, 30% concentrate, and 30% Indigofera zollingeriana has the potential to enhance the digestibility CF and promote microbial protein synthesis, all the while reducing CH4 gas emissions (Nurhalimah *et al.,* 2021).

The quality of CP, EE, NDF, ADF, and TDN in feed has a considerable impact on the emissions of CH_4, N_2O, and CO_2 gasses during enteric fermentation. Feed formulations T1 and T2 have the same CP content. The T2 and T3 treatment feed formulae yielded less CH_4 gas than the T1 treatment. The T1 regimen involves the provision of freshly harvested king grass as feed, which poses a greater challenge in terms of digestibility compared to silage. Animals must fight to digest the forage, which increases CH_4 production in the rumen. Silage undergoes pre-digestion by bacteria within the silo, resulting in enhanced digestibility for animals and reduced CH4 emissions (Little, *et al.,* 2017). Feed formula T3 treatment has the highest CP content due to its composition of fermented rice straw and concentrate. Concentrate offers a more extensive nutritional composition and a higher CP level, contributing to the advantageous growth of cows. Elevated levels of concentrate have been observed to decrease CH_4 emissions from enteric fermentation in dairy cows by 20-40% (Boadi *et al.,* 2004). The T3 treatment feed formula had the maximum nutrient absorption efficiency due to its high TDN value, resulting in reduced CH_4 gas generation. A decrease in CH4 production has been linked to a decline in the protozoa population among multiparous dairy cows that were provided with different (Tapio, *et al.,* 2017). GHG emissions are mostly caused by the microbial breakdown of proteins, organic acids, carbohydrates, and soluble lipids in feed and excreta (Rivera and Chara, 2021).

Table 2: The dry matter and organic matter digestibility of feed formulae T1, T2, and T3

Parameter	T1	T2	T3	p<0.05
DMD	55,8±4,02	57,21±8,3	57,64±9,2	0,906
OMD	11,6±2,5	11,63±2,12	12,09±3,39	0,842

Table 3: Total estimation of GHG emissions from in vitro testing of feed formulations for T1, T2, and T3.

Treatment	CH_4	N_2O	CO_2	Total CO_2 equivalent (CO_2eq)
T1	4,049.67	1.76	2,643.93	6,695.36
T2	3,924.28	1.62	2,648.51	6,574.42
T3	3,026.00	1.98	1,807.11	4,835.09

The digestibility of DMD and OMD

The calculation findings for DMD and OMD showed no significant differences across treatments (Table 2). Straw is frequently employed as feed for ruminants. However, it possesses a low protein concentration along with elevated levels of lignin and silica, which complicates its digestibility and diminishes its nutritional benefits. The process of ensiling can enhance the utilization and nutritional quality of straw. The rice straw used in this investigation was fermented with stimulant plus bacteria primarily from the Bacillaceae and Streptococcaceae families. Bacteria in the Bacillaceae family can create enzymes that break down complex components in straw, such as lignin and cellulose. It has been established that Bacillus cereus effectively reduces lignin levels by 89%, leading to an improvement in the nutritional availability (Gu *et al.,* 2024). Meanwhile, Streptococcus pyogenes controls the fermentation pH (potential of hydrogen) of straw feed by pH sensing and virulence factor modulation. The process of acidification may inhibit the proliferation of harmful bacteria, thereby enhancing the safety and regulation of the fermentation process (Fidien *et al.,* 2021). Streptococcus bovis is capable of producing lactic acid through the fermentation of carbohydrates, which subsequently lowers the pH of its environment (Cabrol *et al.,* 2017). Ginting *et al.* (2022) found that feeding fermented rice straw with ecoenzymes produced DMD and OMD levels comparable to dwarf elephant grass.

Total estimation of GHG emissions

The results demonstrated that, whereas T3 could reduce potential GHG emissions by 26.46% from T2 and by 27.78% from T1, the T2 treatment feed formula could only reduce potential GHG emissions by 1.81% from T1 (Table 3). This indicates that replacing concentrate with rice and wheat bran, along with using fermented straw instead of king grass in the feed formulation, can substantially reduce potential greenhouse gas emissions when compared to the scenario where only fermented straw is substituted for king grass in the same feed formulation. During feed processing, feed with a high CP concentration can lower GHG emissions. The process of anaerobic fermentation in feed processing can yield gases that contain a minimum of 50% CH4. This gas is more environmentally stable than CO2 and can be assimilated by plants through the process of photosynthesis (Nugroho *et al.,* 2013).

Fermented straw can be used as an alternative source of animal feed fiber to replace traditional feed, technical solutions are required to improve nutritional quality and digestibility (de Vries *et al.,* 2019). The process of straw fermentation in the feed formulations of treatments T2 and T3 did not influence the DMD or OMD when assessed against treatment T1, which utilized king grass as the fiber sources. Straw fermentation can reduce CH_4 production in animal digestive systems because it alters the structure of the straw, making it easier to digest. Bacillaceae and Streptococcaceae are suitable for the fermentation of straw, in conjunction with various fungal species. *Trichoderma viride* can be utilized to stimulate the fermentation process, improving the quality of rice straw and streamlining nutrition for ruminants (Muwakhid, *et al.,* 2023). Pleurotus ostreatus is preferred for the fermentation of rice straw intended for ruminant feed during the dry season due to its ability to effectively decompose lignin and enhance the nutritional value of the straw

(Datsomor, *et al.,* 2022). Livestock feed with high CP content can reduce GHG emissions, which directly contributes to reducing global warming (Ishak *et al.,* 2019). Indonesia's total GHG emissions in 2022 were 12,40.83 Mton CO_2eq, or around 2.31% of the world's total emissions; 6,758 Mton CO_2eq came from the agriculture sector (Edgar, 2023). The cattle industry produced 26,997 Gg CO_2eq of GHG emissions in 2019. Enteric fermentation accounted for 17,977 Gg CO_2eq of these emissions, manure management for 1,772 Gg CO_2eq, and direct N_2O for about 7,307 Gg CO_2eq (DGCC, 2021). About 433,633 ton per year (t/y) of straw were produced in Karanganyar Regency, Central Java, between 2018 and 2022. Of that amount, 200,677.60 t/y went toward animal feed, 62,643.06 t/y went toward organic fertilizer, and 103,013.03 t/y was not put to use (Arianti *et al.,* 2022). The practice of burning rice straw among numerous rice farmers in Karanganyar contributes significantly to environmental pollution. The practice of open burning of straw emits black carbon, which ranks as the second most significant contributor to global warming following carbon dioxide, and it also poses various health risks to humans (Hafidawati *et al.,* 2017). Inefficient use of straw often leads to anaerobic decomposition in agricultural settings, which can result in the generation of GHG emissions. When straw waste is used as animal feed, it reduces GHG emissions in the agricultural industry, even if it was previously a source of pollution. Biomass obtained from rice straw can be processed biologically to produce bioproducts with enhanced value (Arianti *et al.,* 2024). Utilizing fermented straw as a source of animal feed offers significant economic advantages to farmers. Farmers earned IDR 2,279,979.49 every three months utilizing the fermented straw and rice bran feed formula, with an R/C value of 1.22 (Anisa *et al.,* 2023). Feeding a feed formula containing 40% fermented straw and agricultural waste such as rice bran, coffee husk, tapioca pulp, cottonwood seed meal, and coconut meal with a CF value of 11% yielded a net income of IDR 802,218,00/head/56 days and was economically feasible with an R/C value of 2.3 (Maluyu *et al.,* 2009). The average net income from the fermented straw production business for feed is IDR 317,000/2 weeks, with an R/C ratio of 1.23 (Fitriyah *et al.,* 2021). Straw serves as a viable source of animal feed, thereby diminishing the necessity for additional grazing and forage areas. The utilization of straw in this manner contributes to the preservation of natural ecosystems and mitigates land conversion, which is a significant contributor to GHG emissions. In this study, the T1 treatment feed formula employed 30% king grass as a forage source from total dry matter, and if all cattle rations in Central Java were fed the T1 feed formula, the amount of king grass used would be approximately 1,088.77 thousand t/year. There is no comprehensive life cycle assessment (LCA) data for king grass, but Packchong Napier grass cultivation in Prachinburi Province, Thailand, can be used for comparison, with the carbon footprints of irrigated and non-irrigated plots being 17,182 and 19,138 kg CO_2eq/t, with fertilizer application accounting for the majority of the contribution (Somjai and Suwan, 2020). The utilization of rice straw does not necessitate additional land, and its application could substantially reduce greenhouse gas emissions associated with agricultural land practices (de Vries *et al.,* 2019). According to Hart *et al.,* (2022), rising food feed competition over limited arable land resources to produce forage for ruminant animals has resulted in increased demand for silage feed. Utilizing straw as a feed source for livestock can significantly reduce the need for arable land dedicated to animal husbandry (Singh *et al.,* 2022). The use of straw reduces the need for land to cultivate forage crops specifically for animal feed, freeing up ground for other agricultural commodities or conservation (Farda *et al.,* 2015). The use of straw can have an indirect effect on decreasing greenhouse gas emissions linked to the application of fertilizers and the management of land designated for forage crops (Singh *et al.,* 2019). The application of fermented rice straw improves soil health, water use, and biodiversity. Utilizing fermented straw as animal feed can significantly decrease the anaerobic decomposition occurring in agricultural fields. When straw is left in situ, it has the potential to lower oxygen concentrations in the soil, thereby hindering the activities of microorganisms that contribute positively to soil fertility (Shi *et al.,* 2024). The use of fermented straw as feed indirectly reduces the use of forage, lowering water consumption in the forage producing process. Water use efficiency is related to prioritizing more important needs and reducing the risk of production failure, particularly in locations with acute water scarcity (Santoso *et al.,* 2023). In general, forage production predominantly occurs on marginal lands. The utilization of fermented straw as animal feed

serves to indirectly minimize the need for expanding or converting additional land for forage cultivation, thereby mitigating potential disrupt biodiversity. Proper husbandry management, including quality feed supply and livestock technology advancement at the farm level, should be implemented with caution to boost productivity and safeguard the environment from GHG emissions in the livestock industry (Defar *et al.,* 2018). The findings of this study contribute to the advancement of methodologies for estimating potential associated with three distinct feed formulations, each characterized by differing feed qualities commonly utilized by cattle producers in Central Java region. There are still restrictions in the range of feed formula combination treatments, which do not represent all feed formulae provided, depending on the resources of each location in Central Java. Further comprehensive investigation is necessary to ascertain the optimal number of sites for livestock centers and rice cultivation, the differences in feed formulations influenced by regional resource availability, the economic viability of integrating straw with diverse feed components, and the LCA of straw as a feed ingredient, considering geographical, social, economic, technological, and environmental factors. The findings of this study serve as a valuable reference for both farmers and policymakers engaged in the management of low greenhouse gas (GHG) emission cattle farming. Furthermore, these findings can act as a foundation for more extensive investigations aimed at enhancing livestock productivity and contributing to the agricultural sector's value, all while ensuring environmental sustainability.

CONCLUSION

The study's originality is in the revelation of possible GHG emissions from enteric fermentation of feed formulas with varying feed quality routinely used by cattle producers in the Central Java region using in vitro testing and precision gas chromatography tools. The study found that the composition of the feed formula had a significant impact on the generation of greenhouse gas emissions resulting from enteric fermentation. The results revealed that feed quality with the formula 30% king grass + 35% rice bran + 35% wheat bran (T1) was equal to the formula 30% fermented rice straw + 35% rice bran + 35% wheat bran (T2). The formulation of 30% fermented rice straw + 70% concentrate (T3) had approximately 3% more CP than T1 and T2. The DMD and OMD levels did not differ significantly between treatments. Straw is characterized by a low protein content, yet it contains considerable amounts of lignin and silica. During fermentation, the structural components of lignin and silica undergo degradation, resulting in fermented straw that is more digestible and suitable as a feed substitute. Feed formula T2 can reduce potential GHG emissions by 1.81% from T1, whereas T3 can reduce potential GHG emissions by 27.78% from T1 and 26.46% from T2. The application of fermented straw may significantly mitigate greenhouse gas emissions resulting from enteric fermentation and the pollution associated with unused straw waste. Additionally, it has the potential to decrease land utilization and the greenhouse gas emissions linked to forage plants. This suggests that using fermented straw as animal feed has an indirect beneficial impact on lowering GHG emissions from unutilized agricultural waste, and that there are chances to use other agricultural waste, such as corn and soybeans, in the Central Java region. The incorporation of fermented straw into animal feed contributes positively to soil health, enhances water use efficiency, and promotes biodiversity. Efforts to employ fermented straw as a low-GHG emission feed must be followed by improved feed quality through technological advancements in fermentation and formula combining, particularly the use of concentrates. Further in-depth research is needed on variations in feed formulas based on regional resource differences, the economic feasibility of using fermented straw combined with various feed ingredients, and the LCA of straw utilization as a feed ingredient in terms of geographical, social, economic, technological, and environmental dimensions. This document serves as a valuable reference for farmers aiming to enhance the quality of their feed formulations; also provides essential information for policymakers focused on managing low GHG emission cattle farming by utilizing fermented straw through mapping of cattle farming and rice production centers, socialization of low-GHG emission cattle feed management, and facilitation of the availability of technology and assistance in managing low-GHG emission livestock; and as a reference for more comprehensive research to support efforts to increase livestock productivity and the added value of the agricultural sector that is environmentally friendly and sustainable.

AUTHOR CONTRIBUTIONS

S. Sulistyo conceptualized the research, literature collection and analysis, methodology development, data collection, validation and analysis, visualization, article drafting, article review and finalization. P. Pranoto conceptualized the research, methodology development, data validation, visualization, article review and finalization. E. Mahajoeno conceptualized the research, methodology development, data validation, visualization, article review and finalization. S.H. Pranolo conceptualized the research, methodology, data validation, visualization, review and finalization of the article. A. Sofyan conducted the study conceptualization, methodology development, data validation, visualization, article review and finalization. H. Herdian conducted literature collection and analysis, methodology development, data validation and analysis, visualization, article draft preparation, article review and finalization. B. Haryanto conducted literature collection and analysis, methodology preparation, data collection, validation and analysis, visualization, article draft preparation, article review and finalization. R.H. Praptana conducted literature collection and analysis, methodology preparation, data validation and analysis, visualization, article draft preparation, article review and finalization.

ACKNOWLEDGEMENT

The in vitro experiment was conducted, National Research and Innovation Agency of Indonesia for the laboratory facility in Playen, Gunungkidul. Gas analyzed at the Greenhouse Gas Laboratory, Indonesian Agricultural Environment Instrument Standard Testing Institute (IAESTI), Pati, Central Java, Indonesia for supporting methane and carbon dioxide analysis.

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

©2024 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	Degrees Celsius
$(NH_4)HCO_3$	Ammonium hydrogen carbonate
ADF	Acid detergent fiber acid detergent fiber
BPS	Badan pusat statistik [statistics indonesia]
BRIN	Badan riset dan inovasi nasional [national research and innovation agency]
$C_{12}H_6NNaO_4$	Resazurin
$CaCL_2.2H_2O$	Calcium chlorid 2-hydrate
CF	Crude fiber
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
$CoCL_2.6H_2O$	Cobalt (II) chloride hexahydrate
CP	Crude protein
CRD	Completely randomized design
DMD	Digestibility of dry matter
DMRT	Duncan multiple range test

EE	Extract ether
$FeCl_3.6H_2O$	Ferric chloride hexahydrate
g	Grams
GC	Gas chromatography
GHG	Greenhouse gas
IAESTI	Indonesian Agricultural Environment Instrument Standard Testing Institute
IPCC	Intergovernmental panel on climate change
IRRI	International rice research institute
K_2HPO_4	Potassium hydrogen phosphate
Kg	Kilograms
kg CO_2 *eq/t*	Kilograms carbon dioxide equivalent per ton
kg/head/d	Kilogram per head per day
LCA	Life cycle assessment
$MgSO_4$	Magnesium sulfate
mL	Milliliters
mm	Millimeters
$MnCl_2.4H_2O$	Manganese (II) chloride tetrahydrate
Mton	Metric ton
N_2O	Nitrous oxide
$Na_2S.5H_2O$	Sodium sulfide pentahydrate
$NaHCO_3$	Hydrogen carbonate
NaOH	Sodium hydroxide
NDF	Neutral detergent fiber
^oC	Cellcius
OM	Organic matter
OMD	Organic matter digestibility
pH	Potential of hydrogen
PM	Particle matter
ppm	parts per million
R/C	Revenue to Cost
RDP	Rumen degradable protein
RUP	Rumen undegradable protein
t	Tons
t/y	Tons per year
T1	Treatment one
T2	Treatment two
T3	Treatment three
TDN	Total digestible nutrients
VFA	Volatile fatty acids
VOCs	Volatile organic compounds

REFERENCES

Anisa, S.A.; Ambarsari, W.; Mahmud, Y.; Suherman, A., (2023). Analisis usaha penggemukan sapi Peranakan Ongole (PO) dengan pemberian ransum dedak padi dan jerami fermentasi amoniasi di Kelompok Ternak Tunggal Rasa, Desa Majasari, Kecamatan Sliyeg, Kabupaten Indramayu. Agri Wiralodra 15(1): 17-25 (**9 pages**).

Aprilliza, M.N.; Anggraeni, Y.N.; Wina. E., (2021). Peranan senyawa katekin dan turunannya dalam memitigasi produksi gas metana pada fermentasi rumen. Wartazoa. 31(1): 13-22 **(10 pages)**.

Arianti, F.D.; Triastono, J.; Pertiwi, M.D.; Prabowo, A.; Prasetyo, T.; Chanifah.; Haryanto, B.; Megawati; Astuti, W.; Djarot, I.N.; Santoso, A.D.; Wijayanti, S.P., (2024). Renewable energy potential of rice straw and paunch manure as bioethanol feedstocks in Central Java, Indonesia. Case study: Chem. Environ. Eng., 9: 100677 **(9 Pages).**

Boadi, D.; Wittenberg, K., (2002). Methane production from dairy and beef heifers fed forages differing in nutrient density using the sulphur hexafluoride (SF 6) tracer gas technique. Can. J. Anim. Sci., 82(2): 201-206 **(6 pages).**

Boadi, D.; Benchaar, C.; Chiquette, J.; Massé, D., (2004). Mitigation strategies to reduce enteric methane emissions from dairy cows: update review. Can. J. Anim. Sci., 84: 319-335 **(17 pages).**

BPS, (2024). Jawa Tengah Province in figures 2023. Statistics of Jawa Tengah Province **(1090 pages).**

Cabrol, L.; Marone, A.; Tapia-Venegas, E.; Steyer, J.P.; Ruiz-Filippi, G.; Trably, E., (2017). Microbial ecology of fermentative hydrogen producing bioprocesses: useful insights for driving the ecosystem function. FEMS Microb. Rev., 41(2): 158–181 **(24 pages)**

Camacho, L.F.; Silva, T.E.; Palma, M.N.N.; Assunção, A.S.; Rodrigues, J.P.; e Silva, L.F.C.; Detmann, E., (2019). Evaluation of buffer solutions and urea addition for estimating the in vitro digestibility of feeds. J. Anim. Sci. 97: 922–931 (**10 pages**).

Castro-Montoya, J.M.; Dickhoefer, U., (2020). The nutritional value of tropical legume forages fed to ruminants as affected by their growth habit and fed form: A systematic review. Anim. F. Scie. Tech., 269 **(14 pages)**

Cui, Y.; Liu, H.; Gao, Z.; Xu, J.; Liu, B.; Guo, M.; Yang, X.; Niu, J.; Zhu, X.; Ma, S.; Li, D.; Sun, Y.; Shi, Y., (2022). Whole-plant corn silage improves rumen fermentation and growth performance of beef cattle by altering rumen microbiota. Appl. Microb. Biotech. 106: 4187–4198 **(12 pages).**

Datsomor, O.; Gou-qi, Z.; Miao, L., (2022). Efect of ligninolytic axenic and coculture white-rot fungi on rice straw chemical composition and in vitro fermentation characteristics. Sci. Rep., 12: 1129 **(8 pages)**

Defar, G.; Mengistu, A.; Berhane, G., (2018). Estimation of livestock methane emissions in the extensive crop-livestock farming

areas of Bale Highland, Oromia, Ethiopia. Eur. Jour. of App. Sci., 10 (4): 89-98 (**10 pages**).

de Vries, J.; Bourgot, C.L.; Calame, W.; Respondek, F., (2019). Effects of β-Fructans fiber on bowel function: A systematic review and meta-analysis. Nutr., 11: 91 **(17 pages).**

Dhakal, R.; Copani, G.; Cappellozza, B.I.; Milora, N.; Hansen, H.H., (2023). The effect of direct-fed microbials on in-vitro rumen fermentation of grass or maize silage. Ferment., 9: 347 **(15 pages).**

Dhia, K.S.; Umar, M.; Mahesti, G.; Purnomoadi, A., (2015). Potensi cemaran nitrogen ke udara dari feses sapi potong dengan level protein intake yang berbeda. Pros. Sem. Nas. Tekn. Pet. dan Vet., 2015: 306-311 **(6 pages).**

DGCC, (2021). Directorate general of climate change. Statistik. **(157 pages).**

Edgar, (2023). Emissions gap report 2023. EDGAR: The emissions database for global atmospheric research. Emissions Database for Global Atmospheric Research. **(108 pages).**

Farda, F.T.; Laconi, E.B.; Mulatsih, S., (2015). Feed potential of agriculture waste for beef cattle development in Kuningan Regency, West Java. J. Ind. Trop. Anim. Agric., 40(3): 167-175 **(9 pages)**

Fidien, K.A.; Manguntungi, B.; Sukmarini, L.; Mustopa, A.Z.; Triratna, L.; Kusdianawati, F., (2021). Diversity analysis, identification, and bioprospecting of Lactic Acid Bacteria (LAB) isolated from Sumbawa horse milk. Biodiversity. 22: 6 **(8 pages).**

Fitriyah, A.; Harmayani, R.; Jamili, A.; Mariani, Y.; Kartika, N.M.A.; Isyaturriyadhah., (2021). Economic analysis of business processing rice straw waste into ammoniation feed in Batu Kuta Village, West Lombok. J. Agri Sains., 5(01): 60-67 (**8 pages**).

Gaviria-Uribe, X.; Bolivar, D.M.; Rosenstock, T.S.; Molina-Botero, I.C.; Chirinda, N.; Barahona, R.; Arango, J., (2020). Nutritional quality, voluntary intake and enteric methane emissions of diets based on novel cayman grass and its associations with two leucaena shrub legumes. Front. Vet. Sci., 7: 579189 **(12 pages).**

Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G., (2013). Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. FAO, Rome. **(139 pages).**

Ginting, Y.R.; Umar, S.; Ginting, N., (2022). Effect of fermented rice straw with ecoenzymes on digestibility of dry matter and organic matter in local sheep. J. Pet. Integr. 10(01): 71-77 (**7 pages**).

Goopy, J.P.; Korir, D.; Pelster, D.; Ali, A.I.M.; Wassie, S.E.; Schlecht, E.; Dickhoefer, U.; Merbold, L.; Butterbach-Bahl, K., (2020). Severe below-maintenance feed intake increases methane yield from enteric fermentation in cattle. Br J Nutr., 123(11): 1239-1246 **(8 pages)**

Gu, J.; Qiu, Q.; Yu, Y.; Sun, X.; Tian, K.; Chang, M.; Wang, Y.; Zhang, F.; Huo, H., (2024). Bacterial transformation of lignin: key enzymes and high-value products. Biotech. Biofuels. 17: 2 **(34 Pages).**

Hafidawati; Lestari, P.; Sofyan, A., (2017). Emission factors of black carbon (BC) from rice straw open burning specific to District Cianjur, West Java, Indonesia. Int. J. GEOMATE. 13(36): 126-130 **(5 pages).**

Hart, E.H.; Christofides, S.R.; Davies, T.E.; Stevens, P.L.; Creevey, C.J.; Müller, C.T; Rogers, H.J.; Kingston-Smith, A.H., (2022). Forage grass growth under future climate change scenarios affects fermentation and ruminant efficiency. Sci. Rep., 12: 4454 **(14 pages).**

Hashima, H.; Zubira, M. A.; Kamyab, H.; Zahran, M.F.I., (2022). Decarbonisation of the industrial sector through greenhouse gas mitigation, offset, and emission trading schemes. Chem. Eng. Trans., 97, 511-516 **(6 pages)**

Hristov. B.N.L.; Crompton, A.; Huhtanen, P.; Kreuzer, M.; McGee, M; Nozière, P.; Reynolds, C.K.; Bayat, A.R.; Yáñez-Ruiz, D.R.; Dijkstra, J.; Kebreab,; Schwarm, A.; Shingfield, K.J.; Yu, Z., (2019). Invited review: Nitrogen in ruminant nutrition: A review of measurement techniques. J. Dairy Sci., 102: 5811–5852 **(42 pages).**

IPCC, (2007). Climate Change 2007: Syntesis Report. A report of the intergovernmental panel on climate change. UNEP and WMO. **(112 pages).**

IRRI, (2024). The value of sustainable rice straw management. International Rice Research Institute.

Ishak, A.B.L; Takdir, M.; Wardi., (2019). The contribution of livestock sector for greenhouse gas emission (GHG) on 2016 at Central Sulawesi Province. J. Pet. Ind., 2019 **(8 pages)**

Johnson, K.A.; Johnson, D.E., (1995). Methane emissions from cattle. J. Anim. Sci., 73(8): 2483–2492 **(10 pages).**

Kamyab, H.; Kamarposhti, M.S.; Hashim, H.; Yusuf, M., (2024). Carbon dynamics in agricultural greenhouse gas emissions and removals: a comprehensive review. Carb. Lett. 34:265–289 **(25 pages).**

Kearl, L.C., (1982). Nutrient requirements of ruminants in developing countries. UthahState University. All Graduate Theses and Dissertation. 4183 **(391 pages).**

Kennedy, P.M.; Charmley, E., (2012). Methane yields from Brahman cattle fed tropical grasses and legumes. Anim. Prod. Sci., 52(4): 225-239 **(15 pages).**

Little, S.M.; Benchaar, C.; Janzen, H.H.; Kröbel, R.; McGeough, E.J.; Beauchemin, K.A., (2017). Demonstrating the effect of forage source on the carbon footprint of a canadian dairy farm using whole-systems analysis and the holos model: Alfalfa Silage vs. Corn Silage. Clim., 5: 87 **(19 pages).**

Mahmud, A.; Prima, A., (2021). Inventarisasi potensi emisi metana (CH4) pada peternakan sapi perah di Kecamatan Pujon, Kabupaten Malang. Liveststock Anim. Res., 19(3): 265-273 **(9 pages).**

Mayulu, H.; Suryanto, B.; Sunarso; Christiyanto, M.; Ballo, F.I.; Refa'i., (2009). Feasibility of complete feed based on ammoniated fermented rice straw utilization on the beef cattle farming. J. Indon. Trop. Anim. Agric., 34[1]: 74-80 (**7 pages**).

McAllister, T.A.; Newbold, J.C., (2008). Directing rumen fermentation to reduce methanogenesis. Anim. Prod. Sci., 48: 7-13 **(7 pages).**

Menezes, A.C.B.; Filho, S.C.V.; Silva, L.F.C.; Pacheco, M.V.C.; Pereira, J.M.V.; Rotta, P.P.; Renno, L.N., (2016). Does a reduction in dietary crude protein content affect performance, nutrient requirements, nitrogen losses, and methane emissions in finishing Nellore bulls? Agric. Ecosyst. Environ., 223: 239-249 **(11 pages).**

Muwakhid, B.; Kalsum, U.; Sikone, H.Y.; Rifa'i., (2023). The quality of fermented rice straw with trichoderma viride inoculum. Online J. Anim. Feed Res., 13(2) **(5 pages).**

Naderipour, A.; Abdul-Malek, Z.; Ahmad, N.A.; Kamyab, H.;

Ashokkumar, V.; Ngamcharussrivichai, C; Chelliapan, S., (2020). Effect of COVID-19 virus on reducing GHG emission and increasing energy generated by renewable energy sources: A brief study in Malaysian context. Environ. Technol. Innovation. 20. **(8 pages)**.

Noor, S.; Pramono, H.; Aziz, S., (2014). Deteksi keragaman spesies bakteri metanogen rumen sapi menggunakan kloning gen 16S rRNA dan sekuensing. Scrip. Biol., 1(4) **(8 Pages)**.

Nugroho, D.; Purnomoadi, A.; Riyanto, E., (2013). Pengaruh imbangan protein kasar dan total kecernaan nutrien pada pakan yang berbeda terhadap pemanfaatan energi pakan pada domba lokal. Sains Pet: J. Penelitian Ilum Peternakan. 11(2): 63-69 **(7 pages).**

Nurhalimah, M.; Zain, M.; Elihasridas., (2021). Substitusi konsentrat dengan indigofera zollingeriana pada ransum basal jerami padi amoniasi terhadap kecernaan fraksi serat, populasi protozoa, sintesis protein mikroba dan gas methansecara in-vitro. J. Anim. Sci., 10(1): 54-61 **(8 pages)**.

Pazla, R.; Zain, M.; Despal; Tanuwiria, U.H.; Putri, E.M.; Makmur, M.; Zahera, R.; Sari,L.A.; Afnan, I.M.; Rosmalia, A.; Yulianti, Y.I.; Putri, S.D.; Mushawwir, A.; Apriliana, R.A., (2023). Evaluation of rumen degradable protein values from various tropical foliages using in vitro and in situ methods. Int. J. Vet. Sci., 12(6): 860-868 (**9 pages**).

Prima, A.; Purbowati, E.; Rianto, E.; Purnomoadi, A., (2019). The effect of dietary protein levels on body weight gain, carcass production, nitrogen emission, and efficiency of productions related to emissions in thin-tailed lambs. Vet. World. 12(1): 72-78 **(7 pages).**

Rivera. J.E.; Chará, J., (2021). CH_4 and N_2O emissions from cattle excreta: a review of main drivers and mitigationstrategies in grazing systems. Front. Sustainable Food Syst., 5: 2021 **(17 pages).**

Riyanto, J.; Lutojo; Sunarto, (2020). Aplikasi penggunaan konsentrat pemacu pertumbuhan untuk penggemukan sapi potong di Karanganyar. PRIMA: J. Community Empowering Serv., 4(1): 7-15 (**9 pages**).

Rojas-Downing, M.M.; Nejadhashemi, A.P., Harrigan,T.; Woznicki, S.A., (2017). Climate change and livestock: impacts, adaptation, and mitigation. Clim. Risk Manage., 16: 145–163 **(9 pages)**.

Sakhiya, A.K.; Kaushal, P.; Vijay, V.K., (2023) Process optimization of rice straw-derived activated biochar and biosorption of heavy metals from drinking water in rural areas. Appl. Surf. Sci. Adv., 18: 100481 **(12 pages).**

Salami, S.A.; Moran, C. A.; Warren, H.E.; Taylor-Pickard, J., (2020). A meta-analysis of the effects of slow-release urea supplementation on the performance of beef cattle. Animal. 10: 657 **(25 pages).**

Santoso, A.D.; Arianti, F.D.; Rohaeni, E.S.; Haryanto, B.; Pertiwi, M.D.; Panggabean, L.P.; Prabowo, A.; Sundari, S.; Wijayanti, S.P.; Djarot, I.N.; Kurniawati, F.D.; Sahwan, F.L.; Prasetyo, T.; Barkah, A.; Adibroto, T.A.; Ridlo, R.; Febijanto, I.; Wasil, A.A.; Lusiana, S.; Rosmeika, R.; Heryanto, R.B., (2023). Sustainability index analysis of the organic fertilizer production from ruminat and rice straw waste. Global J. Environ. Sci. Manage., 9(SI): 193-218 **(26 pages)**.

Shi, Y.C.; Zheng, Y.J.; Lin, Y.C.; Huang, C.H.; Shen, T.L.; Hsu, Y.C.; Lee, B.H., (2024). Investigation of the microbial diversity in the oryza sativa cultivation environment and artificial transplantation of microorganisms to improve sustainable mycobiota. J. Fungi. (10): 412 (**15 pages**).

Singh, R.; Patel, M., (2022). Effective utilization of rice straw in value-added by-products: A systematic review of state of art and future perspectives. Biomass Bioenergy. 159: 106411 **(21 pages)**.

Singh, H.; Northup, B.K.; Baath, G S.; Gowda, P.P.; Kakani, V.G., (2019) Greenhouse mitigation strategies for agronomic and grazing lands of the US Southern Great Plains. Mitigation Adapt. Strategies Global Change (2020) 25: 819–853 **(35 pages).**

Sofyan, A., (2017). In vitro gas production kinetics and digestibility of king grass (Pennisetum hybrid) added by organic mineral and natural crude tannin. J. Appl. Anim. Res., 45(1): 122-125 **(4 pages)**.

Somjai, T.; Suwan, C., (2020). Carbon footprint analysis of napier pakchong 1 grass plantation in Prachinburi Province. E3S Web Conference. 141: 2020 **(5 pages).**

Sulistyo, Pangastuti, A.; Setyaningsih, R.; Widyawati, S.D., (2019). Dynamics of the bacterial community in fermentation process of rice straw as animal feed. IOP Conference Series: Earth Environ. Sci., 292: 012026 **(7 pages).**

Suwignyo, B.; Agus, A.; Utomo, R.; Umami, N.; Suhartanto, B.; Wulandari, C., (2016). Penggunaan fermentasi pakan komplet berbasis hijauan pakan dan jerami untuk pakan ruminansia. Ind. J. Community Eng., 01(02): 255-263 (**9 pages**).

Swarnama, T.P.; Velmurugana, A.; Subramania, T.; Ravisankarb, N.; Subashb, N.; Pawarb, A.S.; Perumala, P.; Jaisankara, I.; Roy, S.D., (2024). Climate smart crop-livestock integrated farming as a sustainable agricultural strategy for humid tropical islands. Int. J. Agric. Sustainable. 22(1): 2298189 (**17 pages**).

Tapio, I.; Snelling, T.J.; Strozzi, F.; Wallace, R.J., (2017). The ruminal microbiome associated with methane emissions from ruminant livestock. J. Anim. Sci. Biotechnol., 8: 1–11 **(11 pages).**

Tillman, A.D.; Hartadi, H.; Reksohadiprodjo, S.; Prawirokusumo, S.; Lebdosoekojo, S., (2005). Ilmu Makanan Ternak Dasar. Edisi ke-2. Yogyakarta : Gadjah Mada University Press **(422 pages).**

Tilley, J. M. A.; Terry, R. A., (1963). A two-stage technique for the in vitro digestion of forage crops. J. British Grassland Soc., 18: 104-111 **(8 pages).**

Tomar, K.; Tiwari, S.; Singh, D.; Kumar, D., (2022). Feeding management of ruminant livestock. Smart Agric. Technol., 71-84 **(14 pages).**

Van Soest, P.J.; Robertson, J.B.; Lewis, B.A., (1991). Methods fordietary fiber, neutral detergent fiber, and nonstarchpolysaccharides in relation to animal nutrition. J. Dairy Sci., 74(10): 3583–3597 (**15 pages**).

Woli, P.; Rouquette, F.M.; Long, C.R.; Tedeschi, L.O.; Scaglia, G., (2020). Modification of the summative equation to estimate daily total digestible nutrients for bermudagrass pasture. J. Anim. Sci., 98(11): 354 **(9 pages).**

Zhao, H.; Lv, F.; Liu, G.; Pang, X.; Han, X.; Wang, X.; (2023). Effects of starters with different NDF/starch ratio on rumen fermentation parameters and rumen microorganisms in lambs. Front. Vet. Sci., 10: 1064774 **(16 pages).**

Zhu, X.; Liu, B.; Xiao, J.; Guo, M.; Zhao, S.; Hu, M.; Cui, Y.; Li, D.; Wang, C.; Ma, S.; Shi,Y., (2022). Effects of different roughage diets on fattening performance, meat quality, fatty acid composition, and rumen microbe in steers. Front. Nutr., 9: 885069 **(14 pages).**

AUTHOR (S) BIOSKETCHES

Sulistyo, Ph.D. Candidate, Assistant Profesor, Postgraduate School, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia.
▪ Email: *sulistyouns.79@gmail.com*
▪ ORCID: 0009-0007-3973-3542
▪ Web of Science Researcher ID: KYP-1443-2024
▪ Scopus Author ID: 57222619371
▪ Homepage: http://uns.ac.id

Pranoto, Profesor., Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia.
▪ Email: *pakpranoto@gmail.com*
▪ ORCID: 0000-0002-1626-1147
▪ Web of Science Researcher ID: KYP-8221-2024
▪ Scopus Author ID: 57156656400
▪ Homepage: http://uns.ac.id

Mahajoeno, E., Dr., Lecturer, Departement of Biology, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia.
▪ Email: *edwimahajoeno@staff.uns.ac.id*
▪ ORCID: 0009-0002-3678-6108
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57095929300
▪ Homepage: http://uns.ac.id

Pranolo, S.H., Dr., Associate Professor,4Study Program of Chemical Engineering, Faculty of Engineering,
Universitas Sebelas Maret, Surakarta, Indonesia.
▪ Email: *sunu_pranolo@staff.uns.ac.id*
▪ ORCID: 0000-0001-9127-8697
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 56165980800
▪ Homepage: http://uns.ac.id

Sofyan, A., Ph.D., Researcher, Research Center for Animal Husbandry, National Research and Innovation Agency (BRIN), Cibinong, Bogor, Indonesia.
▪ Email: *ahma053@brin.go.id*
▪ ORCID: 0000-0002-0578-4671
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57136745300
▪ Homepage: https://brin.go.id/

Herdian, H., M.Sc., Researcher, Research Center for Animal Husbandry, National Research and Innovation Agency (BRIN), Cibinong, Bogor, Indonesia.
▪ Email: *hendravit@yahoo.com*
▪ ORCID: 0000-0001-5282-451X
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57136811300
▪ Homepage: https://brin.go.id/

Haryanto, B., M.Sc., Researcher, Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Serpong, Tangerang Selatan, Indonesia.
▪ Email: *bamb073@brin.go.id*
▪ ORCID: 0000-0003-3536-2872
▪ Web of Science Researcher ID: NA
▪ Scopus Author ID: 57190811074
▪ Homepage: https://brin.go.id/

Praptana, R.H., Ph.D., Researcher, Research Center for Food Crops, National Research and Innovation Agency, Cibinong, Bogor, Indonesia.
▪ Email: *rade045@brin.go.id*
▪ ORCID: 0000-0002-6686-3488
▪ Web of Science Researcher ID: JHT-0193-2023
▪ Scopus Author ID: 57203961445
▪ Homepage: https: https://brin.go.id/

HOW TO CITE THIS ARTICLE

Sulistyo; Pranoto; Mahajoeno, E.; Pranolo, S.H.; Sofyan, A.; Herdian, H.; Haryanto, B.; Praptana, R.H., (2024). Utilization of agricultural waste to reduce enteric methane emissions in livestock in tropical environment. Global J. Environ. Sci. Manage., 10(SI): 263-278.

DOI: 10.22034/gjesm.2024.04.17

URL: https://www.gjesm.net/article_714845.html

Global J. Environ. Sci. Manage. 10(SI): 279-302, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Sustainability index for eco-friendly cattle farming in dry climate regions

T. Simamora[1,2,*], M.N. Rofiq[2], L. Hutahaean[2], S. Sio[1], R. Hutapea[2], D. Irawan[2], Suryani[2], R. Diastuti[2], U.N. Thiyas[2], B.A. Correia[3], L.T. Correia[3]

[1] *Animal Husbandry Study Program, Faculty of Agriculture, Science and Health, Timor University, Indonesia*

[2] *Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia*

[3] *Department of Agricultural, Faculty of Agriculture, Timor Lorosa'e National University, Dili, Democratic Republic of Timor-Leste*

ARTICLE INFO

Article History:
Received 07 May 2024
Revised 11 July 2024
Accepted 16 September 2024

Keywords:
Dry climate
Eco-friendly
Multidimensional scaling (MDS)
Sustainability assessment

DOI: 10.22034/gjesm.2024.10.SI.18

ABSTRACT

BACKGROUND AND OBJECTIVES: Cattle farming is an important pillar of dry climate agriculture. Cattle farming has even become the main engine of the community's economy. Currently, there are significant obstacles in the implementation of ecological, economic, technological, and infrastructural dimensions, alongside legal and institutional frameworks, that are essential for promoting sustainable livestock farming practices. Specific studies on different dimensional attributes affecting the sustainability of beef cattle are required. The objective of this study is to investigate different factors within four dimensions that affect the sustainability of cattle farming practices in dry climatic conditions.

METHODS: This study was conducted using an interview approach to respondents using a questionnaire or list of questions. The questionnaire contains questions on 37 dimensional attributes, including ten environmental, ten economic, ten technological and infrastructure attributes, and seven legal and institutional attributes. A range of responses was collected from individuals engaged in livestock management in the dry climatic conditions of Timor Tengah Utara Regency. The data that has been collected is analyzed employing Multidimensional Scaling and expedited appraisal software. To evaluate sustainability and leverage attributes, Monte Carlo analysis and the alternating least squares algorithm are applied.

FINDINGS: The study's outcomes revealed that the sustainability index pertaining to beef cattle farming in dry climates recorded an average score of 53.09 percent. This finding is based on the economic dimension of 45.58 percent, the environmental dimension of 54.18 percent, the technology and infrastructure dimension of 35.15 percent, and the legal and institutional dimension of 77.46 percent. The sustainability index, reflecting the technology and infrastructure aspects, ranks the lowest, primarily because the technological advancements necessary for achieving sustainable livestock farming are still underdeveloped. The availability of livestock waste processing technology is still relatively low and has not been processed optimally. This situation has an impact on the environment.

CONCLUSION: The sustainability index of dry climate beef cattle farming is greatly influenced by the attributes of technology and infrastructure dimensions. The enhancement of sustainability in the future necessitates careful consideration of specific factors, including the accessibility of waste and product processing technologies, advancements in information technology, and the development of road infrastructure. Attributes in the legal and institutional dimensions are the main factors supporting beef cattle's sustainability. Optimizing extension services by increasing the number of livestock extension workers is crucial in accelerating the dissemination of eco-friendly livestock technology and innovation.

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

NUMBER OF REFERENCES
91

NUMBER OF FIGURES
6

NUMBER OF TABLES
2

*Corresponding Author:
Email: *turesimamora@unimor.ac.id*
Phone: +62821 1455 5129
ORCID: 0000-0001-8331-5590

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Dry climate livestock farms are farms run by small farmers in areas where the dry season is 7-8 months of the year (Burrow, 2019). In regions characterized by dry climates, the low levels of rainfall lead to a constrained supply of water. This limitation on water resources poses a critical challenge that influences every aspect of livestock business activities (Halimani *et al.,* 2021). Dry climate farms in Indonesia are generally managed extensively and semi-intensively to optimize meat production (Balaji *et al.,* 2023). In the context of dry climate agriculture, beef cattle serve as the foremost commodity. These farms are mainly located in the eastern part of Indonesia, with Nusa Tenggara Timur (NTT) Province being particularly noted as a central region for the cultivation of beef cattle in arid environments (Kana Hau *et al.,* 2021). The beef cattle commodity commonly reared is a breed of Balinese cattle known as Timor Cattle (TC). This local livestock is different from other cattle in Indonesia. This is due to its high adaptive ability in dry climate (Habaora *et al.,* 2019). In the NTT region, rainfall occurs for roughly five months each year. The pronounced effects of the dry climate on beef cattle farming have impacted various environmental and economic factors. Traditional livestock management also requires the development of technology and infrastructure and optimizing institutional roles in supporting sustainability. The focus of research on livestock sustainability indices has primarily been on fertile land. In opposition, dry land presents distinct characteristics, including variations in climate, soil types, and constraints related to water availability. Analysis of adaptive livestock production systems, including using livestock species more resistant to dry conditions, water harvesting technology, and alternative feed management, must be studied based on sustainability indices. The analysis of socio-economic and institutional factors in dry climate livestock farming is currently limited. The sustainability of these farming systems is fundamentally linked to the local capacity for adopting sustainable agricultural practices. Other waste management problems and energy use in dry climate livestock farming are often overlooked. Research to analyze the multidimensional dry climate livestock sustainability index that combines environmental, social, economic, and institutional aspects to provide a more comprehensive picture. Despite the dry and hot climate, the region has potential for beef cattle development (Ahmad *et al.,* 2022). This makes the area a dryland farming area (Burrow, 2022). One of the aspects affected by this water limitation is feed production, which decreases during the dry season (McLeod *et al.,* 2020). The availability of forage feed throughout the year is a factor that needs to be considered by farmers. Alternatively, there exists considerable development potential within dryland farming. This potential is reinforced by favorable natural resources, including substantial land available for grazing and the opportunity to cultivate locally accessible fodder crops (Rahimi *et al.,* 2022). Dryland farming has developed into one of Indonesia's important beef cattle farming centers, contributing significantly to beef production in Indonesia. Presently, dryland farming encounters several significant challenges, such as the reduced availability of feed during the dry season, which negatively influences the growth of beef cattle. Furthermore, the productivity of livestock is hindered by inbreeding, and there is a lack of technological advancement and innovation in the livestock sector (Tiro *et al.,* 2023). The concept of sustainable development of dryland farming is needed. This includes good feed management, health care, environmental management, and selection of quality breeds to ensure optimal growth and health. Given the vital importance of beef cattle farming in fulfilling the growing demand for beef alongside the increase in human population, the implementation of a sustainable farming system is crucial (Widyas *et al.,* 2022). Sustainable beef cattle farming development is an approach that considers the economic, social, and environmental aspects of its operation (El Ansari *et al.,* 2020). This approach can be done by measuring sustainability using the multidimensional scalling (MDS) method (Mashur *et al.,* 2022). his strategy presents an alternative avenue for generating insights that can aid in the creation of sustainability frameworks for beef cattle in areas characterized by limited moisture. To realize the sustainability of beef cattle farming in drylands requires identifying and analyzing dimensions based on ecology, economy, technology, infrastructure, law, and institutions. The four dimensions need to identify attributes that become factors that determine the sustainability index (Rohaeni *et al.,* 2024). The essential features of sustainable beef cattle development involve the

stewardship of natural resources, strategies for disease prevention and management in livestock, the responsible handling of livestock waste, energy management practices, the use of sustainable technologies, the fortification of farmer cooperative communities, and the facilitation of innovation adoption (Perdinan *et al.,* 2024). Applying a holistic and sustainable approach to beef cattle development is expected to increase livestock production while maintaining environmental sustainability. Research by Kapa *et al*. (2019) showed that technology is needed to sustain local cattle development in drylands. The most important attribute is the extensive rearing system based on the technology dimension. The study demonstrated that in order to promote the sustainability of the beef cattle business, it is crucial to consider six specific attributes. Indrayani *et al.* (2024) stated that the sustainability index of livestock farming in coastal areas is economically, ecologically, and technologically entirely sustainable. The institutional dimension needs to optimize its supporting attributes. Zaied *et al.* (2021) explained that the impact of drought greatly affects the sustainability index of beef cattle, especially the attribute of fluctuations in the selling price of beef cattle in the economic dimension. Mashur *et al. (*2022) identified 90 sustainability attributes with six beef cattle feed bank development dimensions. Based on this identification, in general, the sustainability status of feed banks is less sustainable. Riera *et al.* (2023) suggested that increasing the sustainability index of beef cattle farming needs to be done by collaborating the economic and environmental dimensions. Enhancing the sustainability index of livestock farming can be achieved through the integration of agricultural operations. Attributes in the social and economic dimensions are attributes that determine the status of sustainability (Widjaja *et al.,* 2024). Susanty *et al.* (2021) explained that achieving optimal sustainability in beef cattle development requires targeted efforts to improve critical attributes. This is necessary because attributes affect the sustainability index of each dimension (Allaily *et al.,* 2024). In light of the preceding description, it is imperative to conduct a study on the sustainability of beef cattle farming. This research will provide valuable insights for the government and other involved parties to develop strategies that ensure the sustainable advancement of beef cattle farming in the years to come. Analyzing the sustainability of beef cattle farming in drylands is a study that is needed now. The present study suggests that offering detailed insights into sustainability could facilitate the advancement of small-scale beef cattle farming within the dry climatic conditions of Indonesia. The objectives of this study are: 1) to identify the sustainability of beef cattle in dry climate based on dimensional attributes; 2) to measure the sustainability status of beef cattle farming in dry climate based on the dimensions of ecology, economy, technology, and infrastructure, and law and institutions. This study has been carried out in Timor Tengah Utara (TTU) Regency in 2023

MATERIALS AND METHODS

Site location and *data collection*

This study was carried out in TTU Regency, NTT province, from July to December 2023, as depicted in Fig. 1. The total area of TTU Regency is estimated to be around 2,669.70 square kilometers (km²). This region is classified under the tropical climate category, featuring two significant seasons: the dry season and the rainy season. The dry season usually lasts from April to October, while the rainy season lasts from November to March. Temperatures in this region range between 20 and 30 degrees Celsius (°C), with rainfall varying in different parts of the region but generally between 1,000 and 2,000 millimeter per year (mm/y). Focus group discussions (FGDs) were held with entrepreneurs from several cassava manufacturers in six districts of NTT. A series of questionnaires were issued to specialists in dryland agriculture management, extension workers, heads of livestock administration, experts in beef cattle, and individuals engaged in business activities. FGDs were used to facilitate data collecting at each factoryThe focus group discussions were conducted to investigate the current involvement of business actors in supporting dryland agricultural resources in the study area, with the intention of generating information that would facilitate the identification of sustainability dimensions and characteristics.

Characteristics of the Indonesian dry climate

Dry climate livestock farming has characteristics that are influenced by geographical conditions, climatic conditions, and socio-economic conditions of the community. The climatic conditions of drylands

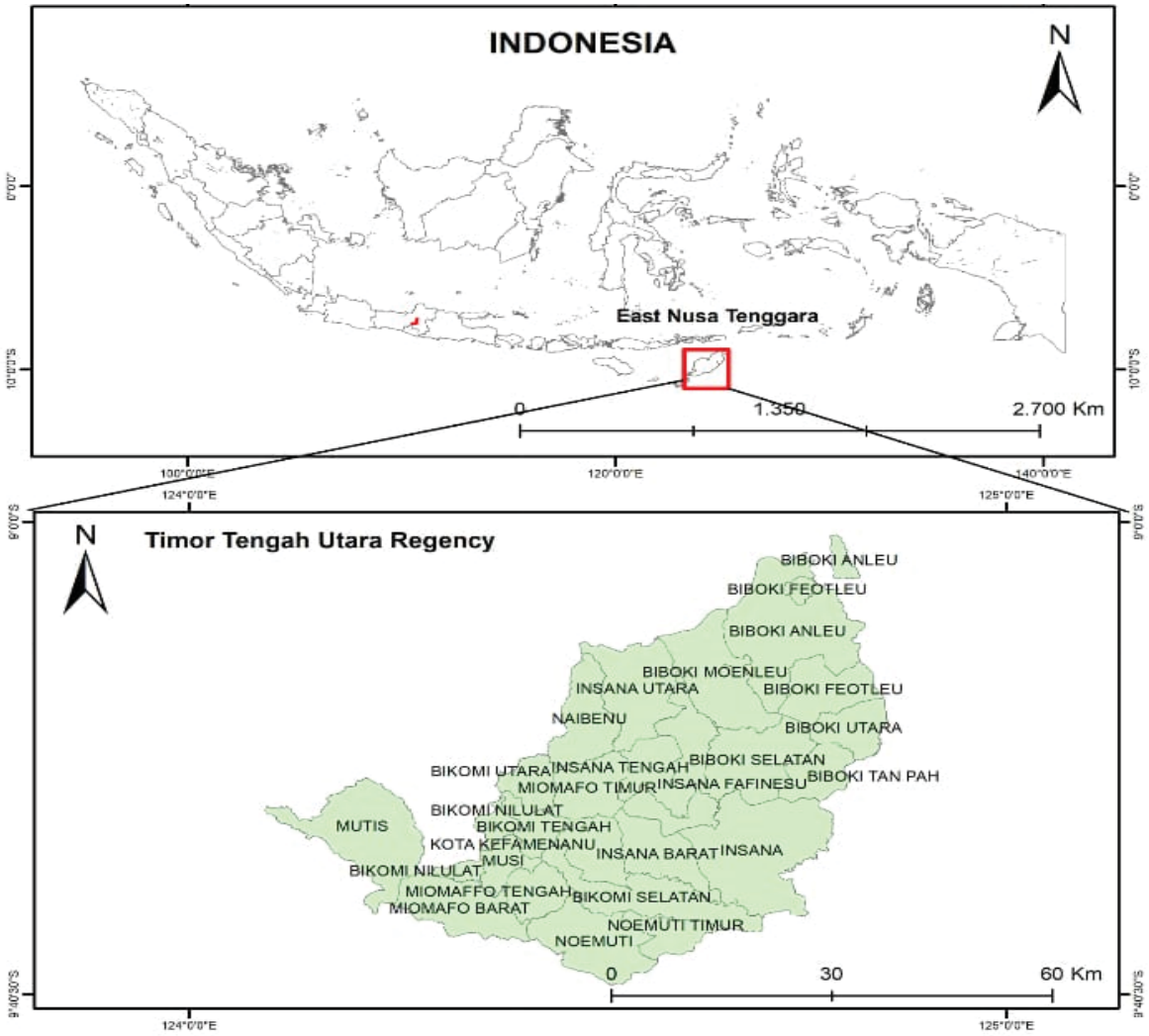


Fig. 1: Geographic location of the study area in dryl climate farming Timor Tengah Utara Regency, Nusa Tenggara Timur Province, Indonesia

have established semiarid practices as a defining feature of animal husbandry, a tradition that persists to the present day. Annual rainfall ranges from 800-1500 mm, with uneven distribution of rain affecting food availability throughout the year. In regions characterized by dry climates, it is common to find Bali cattle breeds that have adapted effectively to these conditions. The prevailing systems of livestock rearing in these farms are largely extensive and semi-intensive.

Data collection

The method of obtaining secondary data involves collecting data from dryland agroforestry guidelines, research journals, and other literature related to income and the sustainability of dryland management. Original information was obtained through observational methods, alongside direct interviews that utilized questionnaires. The respondents were deliberately selected for their active participation, competence, and extensive knowledge regarding dryland agriculture in NTT. Several respondents were determined based on the specified respondents' criteria, including individuals from the village government, the Agriculture Agency, members of farming groups, and various experts associated with dryland agriculture management.

Data analysis

The sustainability analysis of community forest management was conducted using the MDS approach employing the rapid appraisal for private-forestry analysis tool (Rap-Pforest). The identified attributes demonstrate the extent of sustainability across various disciplines, tailored in accordance with the availability of information pertaining to the characteristics of the resources being studied (Pitcher and Preiskhot, 2001). The MDS approach was used to analyze the sustainability of dry climate farming management using the Rapid Appraisal for Dryclimate Analysis tool (Rap-dryclimate). This MDS method has been selected due to its capacity to deliver clear, swift, and objective results regarding the factors that impact duration, which simplifies its implementation in legal environments. There are several steps involved in using MDS, including determining attributes and values through conversation, calculating, and assigning a score in an ordinal range from 0 (fake) to 2 (good) based on the attributes that the respondents carefully considered or based on the available data (primer and secondary). The next step is to do an MDS ordering concerning the leverage factor (leverage factor) analysis of the attributes based on Root Mean Square (RMS) in axis X. The final phase involves conducting a Monte Carlo analysis to assess the influence of scoring errors. The evaluation of measuring instruments is derived from the outcomes of distributing these instruments to various relevant stakeholders beyond the designated respondents. This testing is carried out by distributing questionnaire data on the level of attribute importance, which is then processed using validity and reliability tests. Validity tests are used to determine whether the questions that have been designed are valid or not. Reliability assessments evaluate the extent to which a measuring instrument produces stable and consistent value outcomes. The selected attributes reflect the level of sustainability in each discipline, adjusted based on the availability of information about the characteristics of the studied resources (Pitcher and Preiskhot, 2001). There are four dimensions: environment, economics, technology and infrastructure, and institutional law. This study used 37 attributes (Table 1). A Likert scale-based questionnaire is then utilized to describe the dimensions and qualities. Expert reviewers evaluated the items in the questionnaire, providing scores of 0, 1, or 2 to indicate whether the responses were inadequate, average, or reasonable.

Analysis of the sustainability of dry climate livestock farming

The levels of sustainability performance are divided into four levels, resulting in intervals of 0 percent (%), 25%, 50%, 75%, and 100%. The assessment categories are listed below: 0,00 - 25, poor category, unsustainable; 25,01 - 50, less category, less sustainable; 50,01 - 75, adequate category, relatively sustainable; 75,01 - 100, excellent category: sustainable (Arofi *et al.,* 2015). Leverage analysis serves as a tool for identifying characteristics that are particularly responsive to sustainability considerations. The indicators with the highest root mean square (RMS) values are deemed the most sensitive (Pitcher and Preikshot, 2001). The leverage factors exhibit values ranging from 2% to 8%, suggesting a moderate to favorable influence. If < 2%, the factor is considered not influential, while if > 8%, the factor is considered dominant (sustainable), according to (Pitcher and Preikshot, 2001). Table 2 illustrates the influential factors that play a significant role in the analysis.

The Monte Carlo approach helps calculate errors and estimate uncertainty in MDS. If the discrepancy between the MDS and Monte Carlo values is modest, the MDS analysis for establishing sustainability is 95% accurate.

RESULTS AND DISCUSSION

The progression of beef cattle farming in dry climates, facilitated by the integration of innovation and technology, has the potential to achieve sustainable agricultural outcomes. This strategy is consistent with the global sustainable development goals, focusing on enhancing productivity while adhering to eco-friendly principles. The development of sustainable livestock farming in dry climate is essential, taking into account four main dimensions: environment, economy, technology and infrastructure, as well as law and institutions. According to Stanley *et al. (*2023), there is a great deal of variation in the sustainability results of cattle systems. The variables encompass the types of goods manufactured, the nature and extent of land utilized, as well as the amounts and types of inputs employed. Although the environmental sustainability of animal production has been well studied, there

Table 1: Dimensions and attributes of dry climate farms

Dimensions	Attributes
Environment	1. The beef cattle pen's hygiene 2. Accessibility of agro industrial wastewater treatment facilities for goods derived from beef cattle 3. Accessibility of feed for beef cattle 4. Shifting cultivation activities 5. The ability of natural pastures to carry 6. Land (fertility of the soil) 7. Effective use of resources and energy in systems for raising beef cattle 8. System of raising beef cattle 9. Using agricultural waste to produce animal feed 10. Beef cattle manure is used to make organic fertilizer
Economy	1. Industry availability feed 2. Innovation in product marketing 3. Farmer's place sell his livestock 4. Market demand for beef cattle products 5. Agro-industrial product market farm 6. Transfer of profits from beef cattle farming business 7. Average income of breeders against regency minimum wage 8. Contribution to Original Regional Income for the agricultural sector 9. Contribution to gross domestic product 10. Advantages in cultivating beef cattle farming
Technology and infrastructure	1.Mastery level beef cattle cultivation technology 2. Availability of infrastructure/public facilities and infrastructure 3. Availability of agribusiness facilities and infrastructure 4. Information Technology and transportation 5. Technology for processing beef cattle products 6. Livestock agro-industry waste processing technology beef cattle 7. Feed technology 8. Use of vitamins and probiotics for livestock 9. Post distribution artificial insemination (AI) services 10. Place distribution Animal health post
Legal and institutional	1. Cooperation agreements with other regions about animal husbandry 2. Suitability central and regional policies 3. Livestock farmer groups 4. Availability of local wisdom rules for beef cattle farming 5. Agricultural/livestock extension institutions 6. Management body agropolitan area 7. Livestock Cooperative Beef cattle

Table 2: 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

hasn't been much focus on the combined evaluation of environmental, economic, and social sustainability. To identify opportunities for improvement while avoiding without imposing additional burdens. further research based on this expansive understanding of sustainability is required. According to the analysis conducted using the rapid appraisal of beef cattle (Rap-SAPOT) approach, the ecological dimension shows 54.18% with a status of fairly sustainable, the economic dimension shows 45.58% with a status of less sustainable, the legal and institutional dimension shows 77.46% with a good status and the infrastructure and technology dimension shows 35.15% with a status of less sustainable. The results of the Rap-SAPOT analysis are illustrated in Fig. 2, which reveals the sustainability index values for four

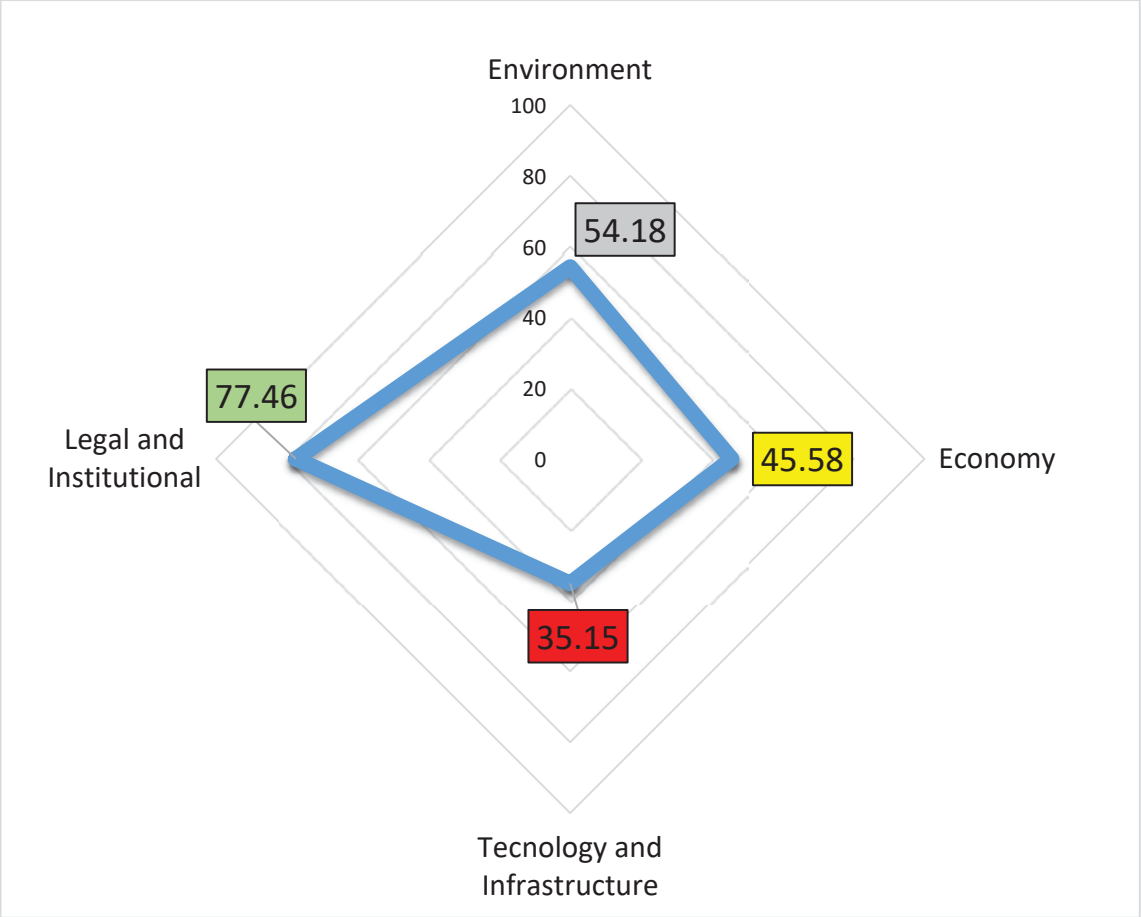


Fig. 2: Multidimensional sustainability of dryland beef cattle farming

dimensions that could be further developed in the future.

Environment dimension

MDS analysis shows that the index value of the ecological dimension is 54.18, the second highest after the legal and institution dimension. The influence of environmental factors on the beef cattle industry has led to modifications in livestock selection aimed at producing resilient breeds capable of thriving in arid climates. This includes the adoption of improved grazing techniques, supplementary feeding strategies, and enhanced management practices (Márton *et al.*, 2023). The environment influences the sustainability of the beef cattle farming business and farmer income in dry climate areas (Rohaeni *et al.*, 2024). The environmental dimension plays an important role in managing beef cattle businesses. Environmental impacts influence the management characteristics of eco-friendly livestock management (Vechi *et al.*, 2022). In Indonesia, especially in its eastern region, environmental issues have not yet emerged as a top priority. The sustainability of beef cattle farming in arid climates is notably affected by two key factors: the hygiene of the beef cattle pen, which has an RMS value of 8.10, and the availability of ago-industrial wastewater treatment facilities for products related to beef cattle, with an RMS value of 7.78. These findings are illustrated in the leverage analysis depicted in Fig. 3. The other attributes do not have a significant impact, but still need to be managed to maintain the ecological dimension in sustainability of beef cattle farming on dry climate. Hygiene within the beef cattle pen is the key element

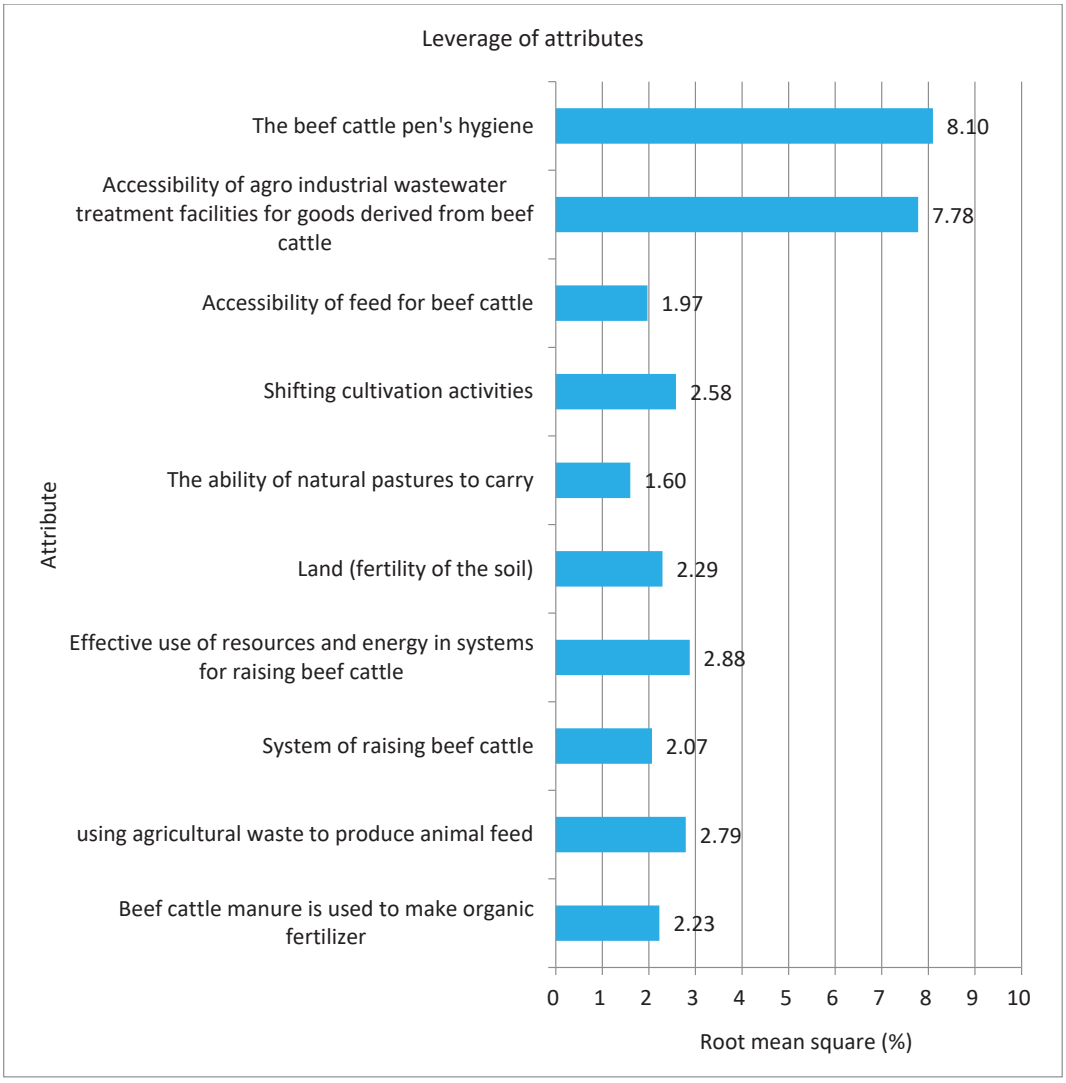


Fig. 3: Leverage attribute for environment dimension

that profoundly affects the sustainability of beef cattle farming in TTU Regency. Even though this area is a dry climate area with limited water sources, the cage's cleanliness must always be maintained. Beef cattle farms in dry climates face challenges in water requirements for barn cleanliness. Farmers are sometimes forced to buy water to clean the barn. To address the challenges of limited air circulation during the dry season, farmers ensure that the barn is cleaned every day. A well-maintained pen is crucial for the well-being of beef cattle, and the cleanliness of the barn environment plays a vital role in determining the quality of beef produced (Moustsen *et al.,* 2023). Cows that live in clean pens tend to have better health and a lower risk of contamination, which can affect the meat quality (Brown *et al.,* 2023). Clean and orderly pens help increase beef cattle production efficiency (Pampori *et al.,* 2023). Animals that inhabit a clean environment are likely to experience superior growth, more effective feed utilization, and elevated reproductive rates. The establishment of wastewater treatment industries for livestock in the TTU Regency is vital for promoting sustainability (Grell *et al.,* 2023).

Several reasons why this is important include;

waste from livestock, including liquid waste, can pollute groundwater and rivers if not appropriately treated (Vaishnav *et al.,* 2023). The wastewater treatment plays a crucial role in purifying waste prior to its discharge into the environment, thereby mitigating its adverse effects on ecosystems and public health (Ibekwe *et al.,* 2023). Livestock waste that is not processed correctly can be a source of disease for animals and humans (Richards *et al.,* 2023). Proper waste disposal is essential for lowering the likelihood of disease transmission, which in turn supports the well-being of farms and their surrounding areas (Koyun *et al.,* 2023). Waste from livestock can be processed into alternative energy sources or organic fertilizers (Odejobi *et al.,* 2023). The wastewater treatment industry can help optimize the utilization of such waste, increase resource efficiency, and promote circular economy principles (Smol, 2023). Considering these various elements, the establishment of wastewater treatment industries for livestock is vital for maintaining the long-term viability of the livestock industry. This attribute is closely related to the supporting attribute of the availability of beef cattle waste processing technology in the technology and infrastructure dimensions. Both attributes are essential parameters in the sustainability of dry-climate beef cattle. The role of these two attributes plays a crucial part in enhancing the income of livestock farmers by facilitating the sale of organic fertilizer produced from livestock waste. The availability of this livestock wastewater processing industry is intended to accommodate and process liquid waste produced by livestock farms in the TTU Regency. This waste includes animals, urine, and other waste that can pollute the environment if not managed properly. The process entails the filtering, isolating, and diminishing of hazardous substances found in waste, which contributes to a reduction in their adverse environmental impact (Sathya *et al.,* 2023). The availability of livestock wastewater treatment industry also serves to help prevent environmental pollution (Qi *et al.,* 2023), including pollution of groundwater and rivers around livestock. It is essential to maintain a balance within local ecosystems to support the health of communities that depend on these natural resources. Furthermore, the incorporation of agricultural waste as animal feed is a key component in promoting the sustainability of beef cattle farming. As has been reported, agricultural waste contains quality nutrients to meet the nutritional needs of livestock (Alan *et al.,* 2023). Using agricultural waste can reduce organic waste and is more economical for farmers. The availability of land for green fodder and the selection of superior livestock are essential factors in maintaining the sustainability of beef cattle farming (Tulu *et al.,* 2023; Ayalew *et al.,* 2023). Having enough land to grow forage, including grass, legumes, and hay, is crucial for satisfying the dietary needs of beef cattle. This forage acts as the primary nutritional resource for the cattle, impacting both their health and productivity levels (Henn *et al.,* 2024). The combination of land availability for green fodder and the selection of superior livestock is an essential strategy for maintaining the sustainability of beef cattle farming. This ensures that livestock can access sufficient and quality feed while optimizing production potential to meet market demand sustainably. Optimizing local feed plants such as lamtoro teramba, which is resistant to heat stress and can grow in dry climates, is an effort farmers make to meet feed availability, especially in the dry season. By implementing regular pruning, fresh lamtoro leaves can be sourced continuously throughout the year. Enhancing livestock productivity involves leveraging feed production, especially within pasturelands. The government still possesses adequate pasture areas that are advantageous for all livestock producers. The government has begun implementing a sustainability-based livestock policy by presenting a livestock integration program with agriculture. One of the government's programs in supporting the poverty of beef cattle farming is the expansion of hybrid corn planting that is resistant to dry climate conditions and supported by sprinkler technology. This policy aims to boost the output of feed concentrate from corn and optimize the use of corn residues for silage. Furthermore, the processing of livestock waste into organic fertilizer significantly enhances the sustainability of this integrated approach.

Economic dimension

Indicators of sustainability in the economic dimension require that the development of a business or product must be competitive and financially profitable economic sustainability is essential for the advancement of businesses that create a range of high-value-added products. This necessity also entails

fostering economic growth at a sufficient pace to enhance the well-being of individuals (Munasinghe, 2019). Some important aspects that must be considered in supporting the sustainability of beef cattle farming include production efficiency (Terry *et al.,* 2021), income diversification (Asante *et al.,* 2018), risk management (Meraner and Finger, 2019), capital and access to finance, increasing added value (Wegari and Gelata, 2021). By evaluating these elements, beef cattle farming can be advanced in a way that guarantees enduring economic sustainability, which serves the interests of farmers, society, and the environment alike. Based on the results of the Rap-beef cattle analysis, the economic dimension is included in the less sustainable criteria with a value of 45.58. The results of the leverage analysis show that there are four most sensitive attributes in the economic dimension, namely the availability of the feed industry (4.67), the availability of livestock marketing innovations (4.64), and the contribution to gross domestic product AI (4.43) and contribution to original income for the agricultural sector (3.68). The high leverage index indicates that these four traits are vital to the evolution of sustainable beef cattle farming practices (Fig. 4). As the global population continues to rise and the demand for food escalates, the feed industry will play a crucial role in ensuring the sustainability of beef cattle farming. This must be addressed in the context of climate change, evolving socioeconomic factors, the growing influence of

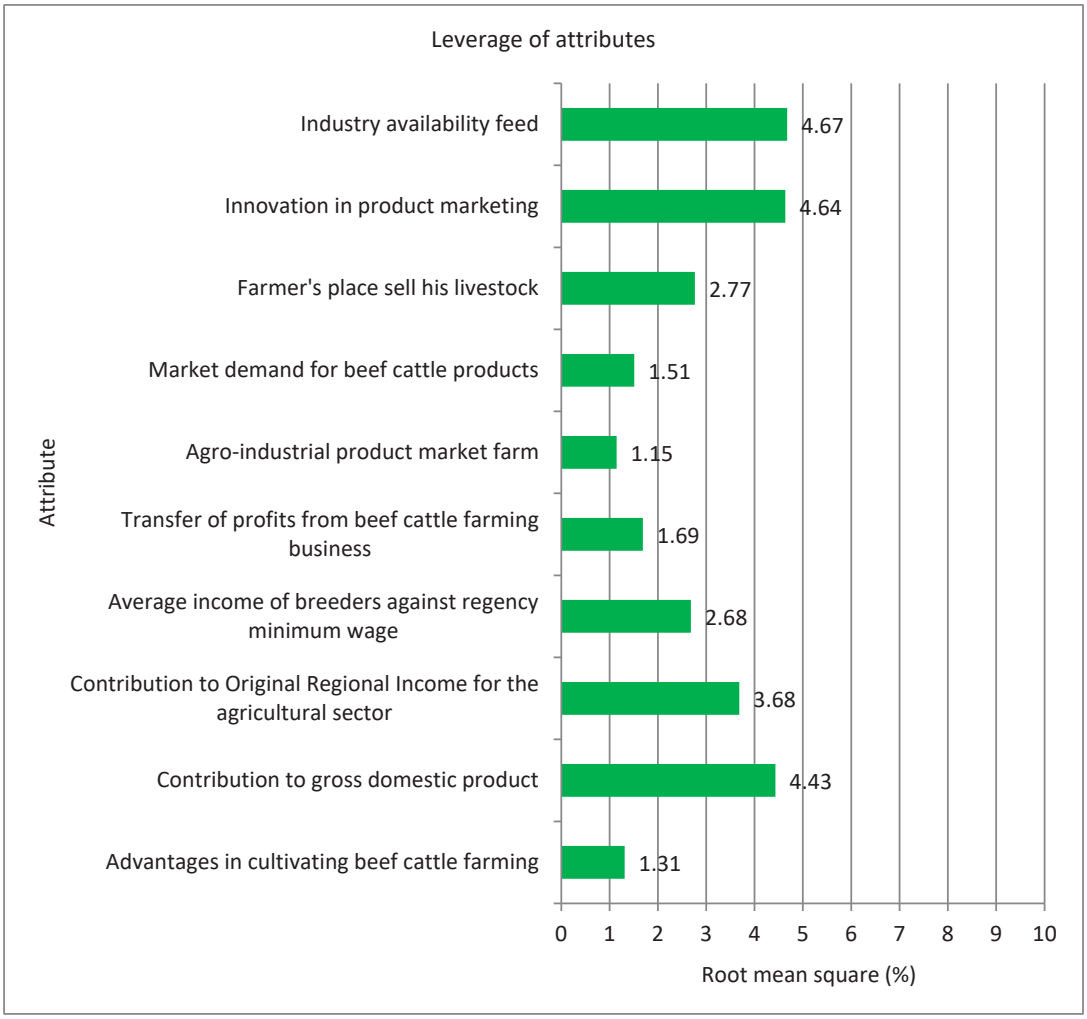


Fig. 4: Leverage attribute for economic dimension

media, and ongoing initiatives aimed at enhancing efficiency (Uddin and Kebreab, 2020; Coffey *et al.,* 2016; Clark *et al.,* 2020). The availability of animal feed affects the quality and productivity of beef cattle (Bunmee *et al.,* 2018). A balanced nutritional regimen for beef cattle leads to superior growth, greater meat output, and an overall improvement in their health condition (Pighin *et al.,* 2016). NTT Province is one of the centres of beef cattle farming, but the results of feed potential mapping show that the region is a feed deficit area, one of the efforts that need to be done is to develop a cheap complete feed industry with local raw materials (Ilham, 2015). The availability of the animal feed industry not only increases livestock productivity and farmers' income, but also reduces dependence on feed supplies from outside the region, thereby increasing local feed security. The significance of the animal feed industry lies in its ability to foster innovation and progress in the development of feed formulations that are both efficient and environmentally friendly, focusing on the incorporation of local raw materials and enhanced processing techniques. The attribute of the availability of the feed industry is closely related to the attribute of the availability of feed processing technology in the dimensions of technology and infrastructure. Farmers greatly need the feed industry's existence to continuously ensure feed availability, mainly concentrate feed, at a more competitive priceTo establish an eco-friendly feed industry, it is essential to adopt modern technologies that effectively address the requirements of a dry climate. The availability of a feed factory that can produce concentrate feed according to the formulation of beef cattle needs is greatly needed to provide for the needs of farmers. This condition will have an impact on the ease of access for farmers to buy cheaper livestock feed rations, which can reduce production costs. According to studies focused on duck business development, the viability of livestock operations is significantly affected by the presence of locally sourced feed (Hutahaean *et al.,* 2022; Bakrie *et al.,* 2023). By utilizing local resources, the animal feed industry can also reduce unemployment by creating jobs and contributing to economic growth. In addition, using local ingredients in the animal feed industry can maintain the sustainability of natural resourcesAccording to the research conducted by Chia *et al.* (2019), insects offer promising potential as affordable, high-quality, and sustainable components for animal feed. The inclusive business model of animal feed from insect raw materials can contribute to solving the environmental, economic, and social problems of developing countries. Ilham (2015) stated that using biomass or waste from plantations as a source of animal feed is an alternative to solving the limitations of green fodder. Significant by-products are produced by the oil palm, coffee, cocoa, coconut, and rubber plantation subsectors, and feed processing technology is employed to develop concentrated feed that maintains a balanced nutritional composition (Aswanto *et al.,* 2023). Marketing innovation in product development has a positive role in increasing profits and product-added value. The availability of marketing innovations is essential for business sustainability, namely by increasing accessibility to marketing institutions, product diversification, creating strong branding, unique product offerings, and market differentiation (Hermansyah *et al.,* 2023). Innovations in marketing will emerge through the integration of digitalization and technology, enhanced training and education, collaborative partnerships and networks, improved infrastructure and logistics, favorable government policies, and the availability of funding, and financing. In the context of beef cattle farming, the relationship between the availability of product innovation attributes and product processing technology attributes is significant to improve the efficiency, quality, and competitiveness of beef products. Enhanced beef processing methods empower livestock companies to deliver meat products of higher quality. For example, precision cutting, cooling, and packaging technology can improve meat quality, extend shelf life, and maintain product cleanliness. The existence of product processing technology is also related to the availability of product innovations that have a high health value, such as low-cholesterol meat. By employing the appropriate processing technology, it is possible to manufacture these innovative products in significant volumes without compromising on quality. Processing technology allows product diversification in the beef cattle industry, such as producing meat with various levels of tenderness, fat content, or unique cuts to meet different market tastes. By diversifying, livestock companies can generate additional value as they pursue innovation in different market sectors. Degila

et al. (2023) stated that the digital transformation of agriculture in African countries can improve food security and economic growth. Adequate infrastructure support for mobile internet usage is a key element in fostering the growth of digital agriculture. To be competitive and self-sufficient in the global e-economy, a country must accelerate change by implementing digital agriculture through effective governance and the synergy of policy programs in various sectors. Beef cattle farmers in North Central Timor District mainly market their products to one village trader who has become a farmer's regular, and some also because there is a loan relationship as a guarantee for the trader so that the farmer does not sell the cow to another livestock trader. Cattle pricing is influenced by evaluations of the cows' body condition, resulting in selling prices that are often disappointing for farmers, who struggle with limited negotiating power (Lole *et al.,* 2021). The limited accessibility of marketing institutions causes the selling price of livestock at the farm level to remain low compared to the selling price in the market (Gobena, 2017). To facilitate better access to marketing institutions, it is crucial to institutionalize beef cattle farmers. Livestock institutions play an essential role in the sustainability of household-scale livestock businesses.

To leverage marketing innovations, it is essential to expand the range of beef cattle products, incorporating processed meats and additional by-products. Diversification can increase farmers' income and add value to their products. Beef cattle farmers have tended to sell live cattle, and product innovation will increase added value. Processing fresh beef into se'i (smoked beef), shredded beef, and jerky products has the potential to boost the added value for farmers in Kefamenanu (Sikone *et al.,* 2022). The research results by Lole *et al.* (2021) stated that the marketing chain of livestock products, processed meat products, and cattle waste has yet to fully and solidly form in NTT. The sustainability of cattle production and marketing is significantly impacted by village traders, who have a direct effect on the earnings of farmers and those involved in slaughterhouse operations. At the same time, the processing of processed meat products and livestock waste needs to be better managed. Gross domestic product (GDP) is an indicator assessing a region's economic performance and welfare. Conversely, revenue generated locally from the agricultural sector evaluates the region's financial ability to support public programs and services. It encourages the region to increase the local economic potential of agricultural activities. This definition indicates that the contributions of GDP and local own-source revenue derived from the agricultural sector are pivotal variables in evaluating sustainability in the economic context. The agricultural sector in NTT is the largest in labor absorption. it contributes significantly to the gross regional domestic product (GRDP) but has yet to become the primary source of economic growth in the NTT economy (Koylal *et al.,* 2022). As reported by Statistics Indonesia in 2023, NTT Province has the third-highest poverty rate in Indonesia. This economic hardship poses a significant obstacle for beef cattle farmers, limiting their access to the resources necessary for successful business management. Limited resource access to land, quality animal feed, animal health services, and other supporting infrastructure. This limited access hinders the growth and productivity of beef cattle farming, which is a significant source of economic activity in NTT.

Technology and *infrastructure dimensions*

Technology and infrastructure are essential aspects that can influence the sustainability of beef cattle businesses in dry climate regions. The adoption of suitable technologies and the establishment of robust infrastructure can enhance the welfare of beef cattle, boost productivity, ensure adherence to environmental regulations, and support the sustainable growth of livestock enterprises. The technology and infrastructure dimensions have low values because the level of existence and availability of attributes, especially technology and information facilities, is minimal. Areas engaged in livestock farming, predominantly situated in the isolated regions of the Indonesia-Timor Leste border, have not been provided with sufficient road infrastructure. The results of the analysis of the sustainability index from the technology and infrastructure dimensions of beef cattle businesses in the dryland of NTT show that at least 4 (four) essential attributes influence the business's sustainability (Fig. 5). Essential attributes encompass expertise in technology, availability of agribusiness facilities and infrastructure, availability of public facilities and infrastructure,

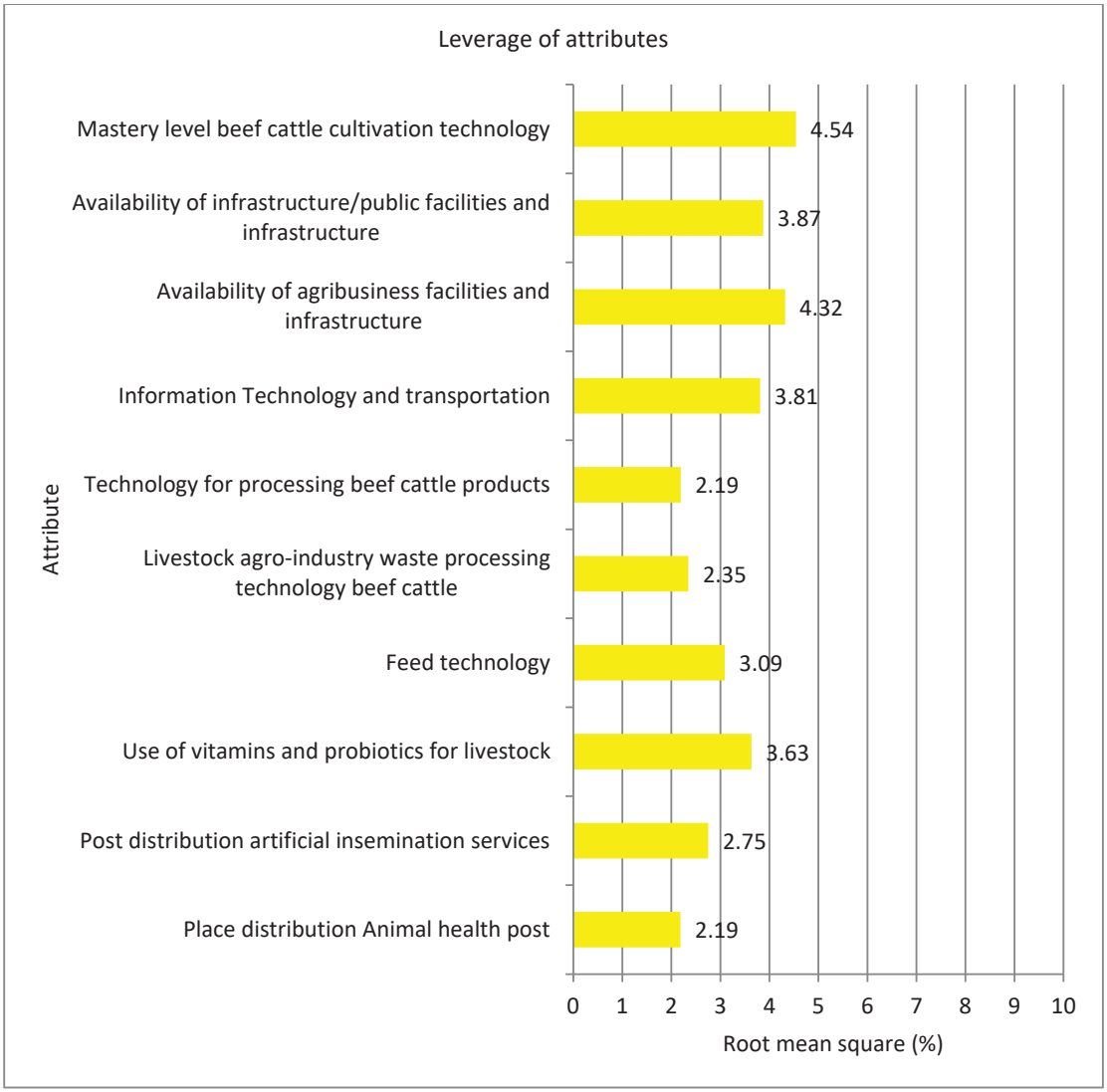


Fig. 5: Leverage attribute for technology and infrastructure dimension

along with developments in information technology and transportation. Mastery of good cultivation technology enables farmers to use optimal livestock management, feeding, and health maintenance practices. The ability of farmers in utilizing technology is closely related to the institutional role attributes of livestock in the institutional dimension. Farmers skilled at using the latest technology are certainly influenced by the role of extension workers in disseminating appropriate technology according to needs. Competent extension services play a crucial role in speeding up the adoption of technological advancements. Farmers may also dramatically boost beef cattle production by implementing modern technology such as livestock health monitoring systems and feed automation. To effectively lower operational costs in beef cattle farming, the implementation of innovative cultivation technology is essential. It can be achieved by enhancing overall production efficiency, optimizing resource utilization, and improving waste management. Terry *et al.* (2021) proposed a strategy aimed at enhancing the efficiency of beef cattle production, emphasizing the importance of management practices, breeding

operations, and the formulation and structure of feed. These strategies must also consider the herd's health and immunity, as well as the need for beef cattle to thrive in a changing environment. Understanding proper cultivation technology can help farmers reduce the risk of disease, accidents, and production failures.Precision, intelligence, and sustainability are the current trends in livestock farming (Zhang *et al.,* 2021). Achieving rapid advancements requires proficiency in intelligent technologies, such as precise feeding mechanisms, environmental regulation, early warning systems for diseases, and remote diagnostic capabilities through the Wearable Internet of Things application. Farmers' ability to master technology must be developed through training. Cattle farmers can no longer raise livestock traditionally and must learn to use technology in the beef cattle business. Breeding and feeding technology must be used to increase production sustainably. Mastery of beef cattle cultivation techniques is essential for ensuring the sustainability of beef cattle and achieving these objectives. Completing waste processing technology for beef cattle farming is essential for ensuring livestock sustainability. Farmers must manage by products or waste generated by beef cattle farming. Cow manure, feed waste, and other waste generated on beef cattle farms can pollute the environment if not properly managed. In arid regions, certain farmers have focused primarily on manures, allowing them to undergo minimal treatment in order to enhance the compost's quality. Following agricultural harvest, farmers utilize different crop byproducts as animal feed, employing cut-and-carry methods to tether and nourish their livestock (Raharjo and Suroyo, 2013). Waste can be processed in a way that does not pollute the surrounding environment by using appropriate waste processing technology, such as anaerobic or aerobic waste treatment systems. The decomposition of cow dung results in the production of methane, a greenhouse gas that can negatively impact the environment. Implementing waste processing technologies can effectively lower greenhouse gas emissions by converting cow dung into a cleaner energy alternative, such as biogas. With the right technology, waste from beef cattle farms can be converted into alternative energy sources such as biogas or biomass energy. This can help reduce reliance on fossil fuels and promote energy sustainability. The improper management of livestock waste poses a significant risk to the environment, leading to potential conflicts with local residents and regulatory bodies. Failure to address waste appropriately may result in legal repercussions, operational limitations, or even the shutdown of farming activities. A lack of equipment for processing beef cow waste can have significant implications for the environment, public health, and the economic sustainability of livestock operations. As a result, Adopting proper waste processing technology is essential for ensuring the sustainability of livestock and the environment. Research conducted by Khoshnevisan *et al.* (2021) indicated that the selection of manure treatment technology needs to be more complex and contentious. A significant number of livestock waste treatment methods concentrate on the solid elements of manure, frequently overlooking the liquid portion that can present environmental hazards. The advancement of technology related to feed provision, particularly in forage, plays a vital role in maintaining sustainable beef cattle production in dry climate areas.

NTT Province is one of Indonesia's driest locations. According to the Kupang City Central Statistics Agency (CSA), the rainy season in NTT lasts only four to five months, i.e., from November to February/ March. Supplying animals with forage year-round is unachievable. To ensure its freshness, forage must be preserved effectively, allowing for its use during times when growth is not possible, particularly in the dry season. To maintain the freshness of forage, appropriate technology that is convenient for beef cattle farmers must be implemented. *Silage* is an animal feed prepared from forage and preserved through fermentation. This method preserves the freshness of forage while maintaining its quality and nutritional content. The quality of silage is fundamentally dependent on the fermentation process that occurs during its production. To improve the quality of forage silage, Ranby and Bakken, (2021) have applied a formic-and propionic acid-based additive to improve grass silage quality, reduce losses, and increase aerobic stability in bunker silos. This study showed that Acid treatment increased dry matter (DM) density by 7% compared with untreated silage. Silage maize is known as the "king of feed" because it is rich in crude protein, carotene, sugar, and other nutrients (Chen *et al.,* 2023). Challenges remain in the preparation of silage material, as

the device frequently encounters blockages in the feeder area. To achieve better energy efficiency, reduce blockages, and enhance the quality of the chopped output, it is crucial to refine the design of the feeder and chopper components of the device. The characteristics of agribusiness facilities and infrastructure play a crucial role in promoting the sustainability of beef cattle farming and should be taken into account. Good agribusiness facilities and infrastructure, such as roads, transportation, storage, and processing facilities, make it easier for farmers to reach markets. Agribusiness facilities determine how beef products are distributed to local, regional, and international markets. Proper processing and marketing infrastructure enables farmers to enhance the value added to cattle products. Farm management must consider facilities for slaughter, packaging, labeling, and efficient distribution approaches. Inadequate or inconsistent transportation infrastructure presents a substantial barrier to the marketing of agricultural products, significantly hindering agricultural development in developing countries. Applications such as the Transport Network Strategic Investment Tool (TraNSIT) developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, will be beneficial. The tool has been applied to map freight movement for agriculture supply chains in Vietnam (maize, cassava) and Indonesia (rice, cattle) (Higgins *et al.,* 2023). A robust transportation infrastructure, particularly roads, is vital for the effective transport of beef cattle and various livestock products from agricultural sites to market or processing centers. Furthermore, this public facility enables farmers in reaching market areas to acquire animal feed, livestock medications, and necessary equipment. The road infrastructure connecting cattle beef business locations in TTU is mainly unpaved. If the rainy season comes, farmers will find it difficult to sell their cattle, and livestock traders who come to buy at the business location will lower prices to compensate for the difficulties in accessing roads used by traders. Access to transportation infrastructure is critical to the sustainability of beef cattle production. The transportation of animals is a critical aspect of animal production and usage, yet it has been identified as a major factor contributing to stress, which can detrimentally affect economic results and animal health. Welfare and stress evaluations during transportation are commonly assessed through behavioral analysis, metabolic activity, hormonal levels, and pathological assessments. Several corrective measures have been tried to lessen the reaction of animals to transport stress, including preconditioning, vitamin delivery, immunization, high-energy diet feeding, and electrolyte therapy (Bhatt *et al.,* 2021). Information technology and transportation attributes are essential in ensuring the sustainability of cattle farming in the TTU Regency. The integration of information technology allows farmers to improve the management and monitoring of their livestock operations. Through the use of livestock management software, they can keep track of the health and condition of their cows, organize feeding schedules, monitor breeding activities, and manage their inventories more efficiently. This may increase productivity and lower operational costs. By adopting information technology solutions such as health sensors and individual identification, farmers can significantly improve their animal health monitoring practices. This enables the early detection of illnesses and other health-related problems, leading to timely interventions and a decreased likelihood of injuries. Information technology improves the integration of producers, distributors, and consumers in the beef supply chain. Precision livestock farming (PLF) combines modern technology with the fundamentals of information technology. The method has spread to several nations since its inception in 2003, although it has yet to be fully embraced (Morrone *et al.,* 2022). Morrone *et al. (*2022) stated that the introduction of the Internet of Things (IoT) and Industry 4.0 has permitted PLF's continuing improvement and development. The presence of information technology infrastructure has significantly influenced the sustainability of livestock enterprises, particularly in the marketing of livestock products. Traditionally, farmers relied on conventional markets for selling their livestock, but the advent of digital information access has transformed this approach. The existence of information technology has made farmers market their livestock through digital platforms. This has activated marketing activities related to economic dimension attributes, which have an impact on reducing transportation costs for marketing livestock.

Legal and *institutional dimensions*

Cattle farming in drylands has a 77.6% sustainability index, indicating the importance of institutions in

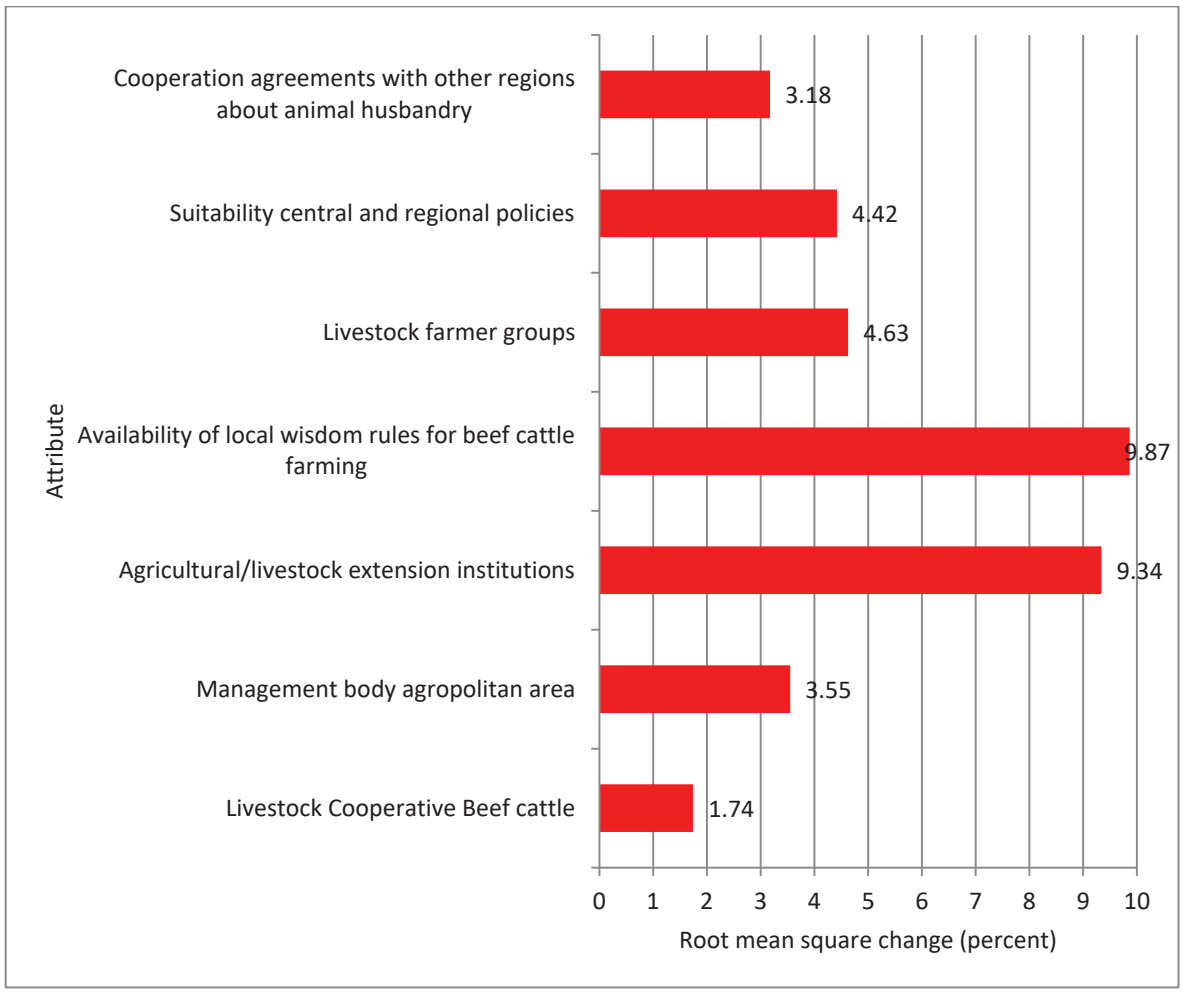


Fig. 6: Leverage attribute for Legal and Institutional technology dimension

promoting efficient, productive, and sustainable growth (Azam *et al.,* 2021). Findings from the analysis indicated that the sustainability index was influenced by various elements, including local wisdom guidelines, organizations dedicated to beef cattle extension, groups of farmers, and the interplay of national and local policies. Fig. 6 below shows the results of the sustainability index and leverage analysis of the legal and institutional components. Local wisdom is crucial for the sustainability of beef cattle in TTU Regency. Communities in the region have developed a deep expertise in managing land and livestock, a tradition of knowledge that has been handed down through the ages. Farmers in TTU use eco-friendly livestock-rearing practices, allowing the cows to develop naturally without much treatment from breeders (Abas *et al.,* 2022). They use local feed that grows all year round. The source of animal feed depends on the friendliness of nature (Firman and Nono, 2021). An additional aspect of local knowledge practiced by farmers involves the utilization of cow dung as a form of organic fertilizer. (Ngongo *et al.,* 2022). Farmers frequently employ organic fertilizers that are cultivated on their properties or designed for horticultural use, and they may also choose to sell these products to create a source of income (Santoso *et al.,* 2023). Farmers also use local herbal herbs for livestock health (Kuralkar and Kuralkar, 2021).

This herb comes from plants that have medicinal properties and have been used for a long time, for

example, papaya leaves for livestock medicine (Osman *et al.,* 2020). Local expertise fosters innovation in the beef cattle market, as seen in the development of Timor cattle that are adapted to withstand dry climatic conditions. By understanding the local ecosystem and livestock needs more deeply, local communities can play a significant role in maintaining environmental balance and livestock welfare, demonstrating a harmonious relationship between humans and their natural environment (Rozaki *et al.,* 2020). The role of livestock extension institutions is vital in enhancing the sustainability of beef cattle within rural communities. They assist farmers in accelerating their socioeconomic development, accessing agricultural knowledge, money, markets, infrastructure, and adopting agricultural advances (Raisa *et al.,* 2020). In TTU Regency, traditional livestock raising is still prevalent, but extension workers provide up-to-date information on best practices including waste management, and environmental conservation (Rohaeni *et al.,* 2024). They deploy advanced technologies for tracking livestock health, assessing animal feed, and managing reproduction. Extension agencies support farmers in mitigating risks and adapting to challenges such as climate change, disease outbreaks, or fluctuations in the market. They provide education and training for farmers to adopt the latest innovations in agriculture. It is essential to expedite the distribution of innovation by implementing comprehensive counseling strategies (Pousga *et al.,* 2022). Counseling must be specific to the context to contribute to the development of the livestock sector (Ahikiriza *et al.,* 2021). The capacity of extension institutions to conduct participatory training with local contextual materials needs strengthening (Ponusamy and Pachaiyappan, 2018). This enables the dissemination of information and experiences, in addition to reinforcing collective solidarity in confronting mutual challenges. Agricultural extension services are provided to small-scale farmers by many parties and through various approaches (Mapiye *et al.,* 2021). Livestock extension workers must function properly and have adequate competence to improve extension both in terms of quality and quantity (Shubeena *et al.,* 2022). According to the insights gathered from the focus group discussion, the primary challenge facing extension services in TTU Regency is the inadequate availability of extension workers within each sub-district. An extension worker has a task for one sub-district, not proportional to the area of work. The implications of this situation will undoubtedly influence the scope of extension activities and diminish the frequency of extension meetings with various groups. Consequently, this will lead to a restricted dissemination of information and a slowed pace of technology adoption within the livestock sector. The process of mentoring and consulting farmers has also become limited, so inadequate access to livestock extension workers and inappropriate information services further reduce farmers' ability to overcome daily challenges and optimize the path to commercialization. This condition has influenced both the environmental and economic aspects significantly. A restricted number of extension workers and the corresponding extension services have a profound impact on farmers' knowledge and skills regarding the implementation of environmentally responsible and efficient livestock farming techniques. One example is the skills of farmers in processing agricultural waste that can be used as animal feed. The lack of extension services provided influences the low abilityIn many developing countries, public extension systems are often burdened by excessive demand, suffer from a deficiency of qualified human resources, and lack the necessary infrastructure, all while witnessing a notable reduction in investment (Mapiye *et al.,* 2021). This could be overcome by increasing farmers' access to information. Extension institutions can make good use of access to information technology, for example through websites, community radios, or mobile phones to disseminate their knowledge and experience (Mustapit *et al.,* 2019). The ability of the extension system to fulfill sustainable agriculture objectives is largely determined by the quality of the extension and consulting services it delivers (Tamsan and Yusriadi, 2022). Livestock extension institutions play an important role in maintaining the sustainability of the beef cattle industry by providing the knowledge, skills, and support needed by farmers to face challenges and improve business performance. Animal husbandry extension institutions must facilitate the establishment of networks between farmers and collaboration with related parties, such as government, universities, industry, and NGOs (Ponusamy and Pachaiyappan, 2018). This enables the dissemination of information and experiences,

which in turn fortifies solidarity in confronting collective challenges. The farmer group attribute significantly impacts the sustainability of the beef cattle farming. Farmer groups are informal institutions in rural areas that foster knowledge and resource sharing among farmers (Raisa *et al.,* 2020). They establish networks of communities to exchange knowledge on optimal practices in livestock management, land stewardship, and sustainable approaches. The introduction of coaching and training programs enables these entities to elevate farmers' expertise in beef cattle management, which in turn fosters superior business management and boosts economic profitability (Abdullah *et al.,* 2019). They can also collaborate with external parties like extension workers or livestock companies to access necessary services and technologies for increased production. This collaboration can lead to increased efficiency, financial profitability (Abdullah, *et al.,* 2019), and the ability to face challenges and obstacles (Raisa *et al.,* 2020). Participation in a farmer group enables farmers to enhance their negotiating power when dealing with various stakeholders, including beef purchasers and suppliers of livestock inputs. This collective approach can lead to improved pricing for their products and greater access to markets, as the formation of these groups is aimed at fostering mutual advantages among the members (Haryadi *et al.,* 2019). The fourth important attribute involves the coherence of policies between national and regional governmental bodies. The success of initiatives aimed at developing beef cattle is largely contingent upon the strategic assistance provided by government policies. The aim for the development of animal farming and health from 2020 to 2024 is to establish a sustainable and competitive agricultural system in Indonesia, which will contribute to the realization of an advanced, autonomous, and contemporary agricultural landscape. The mission is to: 1) increase the availability of quality and sustainable seeds; 2) increase the availability of quality feed on a continuous basis; 3) realize animal health to increase livestock productivity and support public health; 4) improve the safety and quality of animal products and public health; and 5) increase livestock business, processing, and marketing of competitive livestock products. Research findings suggest that the presence of beef cattle plays a vital role in integrated crop-livestock farming systems, contributing to increased productivity and efficiency, all the while upholding the environmental carrying capacity associated with dry land farming practices. The shifting practical agricultural circumstances of farmers, particularly those in dry land areas for the production of peanuts and maize, should garner greater attention from researchers, government institutions, and stakeholders in order to establish sustainable dry land farming systems (Raharjo and Suroyo, 2013). The development of the livestock subsector has a significant impact on rural development and poverty alleviation efforts because the majority of poor people live in the countryside and make a living from farming/farming. To date, the advancement of the farming sub-sector in NTT involves two key roles: 1) Aiming to improve the quality of life for the residents of NTT by increasing agricultural earnings and enhancing community nutrition through better farming techniques and product quality, and 2) contributing to the satisfaction of the national meat requirement by enhancing local farming and agricultural products for consumer communities across different provinces, thereby decreasing the need for foreign exchange in agricultural imports. Concurrently, the local government, via Governor's Decree No. 122 of 2024, has determined a quota allowing for the extraction of 56,260 cattle from NTT. Regulations governing cattle exports must adhere to animal health and transportation standards, which include a ban on the export and slaughter of breeding studs and productive heifers. This figure is lower than pre-2000 allotment, which ranged between 60,000 and 80,000 heads per year. This quota reduction is an attempts to prevent a decline in NTT's cattle population (Priyanto *et al.,* 2020). The consistency of central and regional export quota laws reflects attempts to maintain the NTT cow population, which is a vital step toward sustaining the farming ecosystem's resilience and balance.

CONCLUSION

The analysis and discussion indicate that enhancing the sustainability of beef cattle farming in arid climates necessitates initiatives aimed at improving and optimizing resource potential across four key dimensions. For the environmental dimension, the improvement that needs to be considered is the availability of green fodder throughout the year to meet feed requirements. Implementing a year-round

feed fulfillment strategy can be accomplished by enhancing extension services that provide training to farmers on the production of silage and hay, enabling them to store feed for extended periods. Farmers' feed processing skills must be encouraged to preserve feed when feed production increases during the rainy season. The impact of climate on dry climate significantly affects the sustainability of beef cattle production. The existence of vast pastures, yet lacking in soil fertility, has affected the availability of quality feed provided to beef cattle. The arrangement of grazing fields through the cultivation of quality natural grass can enhance the availability of feed throughout the year. Furthermore, it is crucial to optimize agricultural waste for use as animal feed. From an economic perspective, farmers in dry regions exhibit limited motivation to pursue beef cattle farming as a key source of family income. This indicates that the scale of beef cattle maintenance efforts at the farmer level is not yet optimal in supporting family income. In reality, beef cattle farming is the most resilient endeavor supporting family economies in arid land areas. Another area for improvement within the economic dimension is the expansion of market access, which can be achieved by optimizing the selling price of beef cattle for farmers. In the dimension of technology and infrastructure, the presence of technology and innovation needs to be enhanced, especially in the processing of livestock products that can add value to processed products. So far, farmers have still been selling livestock products in the form of live animals. Currently, animal health posts are not sufficiently established in every district, creating obstacles for farmers seeking veterinary services, especially in managing diseases in beef cattle. In addition, the AI service facilities need to be improved by increasing the number of certified inseminators in each existing sub-district. In terms of legal and institutional dimensions, improvements in the performance of cooperatives in the livestock sector need to be made. The rise in cooperative numbers is facilitated through the enhancement of credit and market services. The government should execute a policy strategy focused on boosting business credit services for livestock farmers, ensuring the availability of low-interest loans. Another policy in optimizing this dimension is increasing the number of extension workers to at least one in each village, including the government's policy of presenting private and independent extension workers to help provide optimal extension services. Improving partnerships with various regions, especially those that import livestock products, is essential for enhancing cooperation. This is done to expand market coverage. The sustainability of beef cattle farming in dry climate has an average sustainability index of 53.09%. This rating comes from the sustainability index values of the environmental dimension at 54.18%, the economic dimension at 45.58%, the technology and infrastructure dimension at 35.15%, and the legal and institutional dimension at 77.46%. In this sustainability index assessment, there are 40 attributes that influence the sustainability of beef cattle. The development plan for beef cattle farming in arid climates must take these attributes into account as they are crucial factors. The outcomes of this study function as a blueprint for establishing collaborative policies that address environmental, economic, technological, and infrastructural factors, in addition to legal and institutional elements.

AUTHOR CONTRIBUTIONS

T. Simamora's role was to conduct literature searches, creating the study plans, supervise on-site data collection, and prepare manuscripts. M N. Rofiq conducted the study design; L. Hutahaean conducted analysis and interpretation; S. Sio contributed to the drafting of the manuscript; R. Hutapea improved the content of the manuscript; D. Irawan critically analyzes the important content value of the manuscript; Suryani produced maps and figures; R. Diastuti contributed to data analysis and provided support; U.N. Thiyas facilitated linking the literature review and data recognition; B.A. Correia drafted the manuscript; L.T. Correia carry out the completion of preparation and refinement of the manuscript as well as degradation of the manuscript

ACKNOWLEDGMENTS

The authors would like to thank the staff involved in the field data collection and the respondents, the cattle breeders, the livestock traders, the heads of the livestock stations in 24 sub-districts and the head of the TTU Livestock Service who gave permission for this Conduct study. The Sustainable Production Systems and Life Cycle Assessment Research Center, the National Research and Innovation Agency and Institute for Research and Community

Service, University of Timor supported the smooth implementation of this study. This study received no specific financial support from funding agencies in the public, commercial or not-for-profit sectors.

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

©2024 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
AI	Artificial insemination
CSA	Central Statistics Agency (CSA)
CSIRO	Commonwealth Scientific and Industrial Research Organization
DM	Dry matter
FGDs	Focus group discussions
Fig	Figure
IoT	Internet of Things
GDP	Gross domestic product
GRDP	Gross regional domestic product
Km²	Square kilometer
mm	Millimeter
MDS	Multidimensional Scalling
NTT	Nusa Tenggara Timur
PLF	Precision livestock farming
Rap-dryclimate	Rapid appraisal for dryclimate analysis tool
Rap-Pforest	Rapid appraisal for private-forestry analysis tool
Rap- SAPOT	Rapid appraisal of beef cattle
RMS	Root mean square
TraNSIT	Transport Network Strategic Investment Tool
TC	Timor cattle
TTU	Timor Tengah Utara

REFERENCES

Abas, A.; Aziz, A.; Awang, A., (2022). A systematic review on the local wisdom of indigenous people in nature conservation. Sustainability., 14 (6): 3415 (**16 pages**).

Abdullah, A.; Jamila, M.; Amidah, A.; Aslina, A.; and Nurlaelah, S., (2019). The role of farmer group on development of beef cattle business. IOP Conference Series.: Earth Environ., Sci., 247(1):012040 (**7 pages**).

Ahmad, M.M.; Yaseen, M,; Saqib, S.E., (2022). Climate change impacts of drought on the livelihood of dryland smallholders: Implications of adaptation challenges. Int. J. Disaster Risk Reduct., 80 (1): 103-210 (**107 pages**).

Ahikiriza, E.; Wesana, J.; Gellynck, X.; Van Huylenbroeck, G.; Lauwers, L., (2021). Context specificity and time dependency in classifying sub-saharan africa dairy cattle farmers for targeted extension farm advice: Case of uganda. Agriculture. 11(836) (**19 pages**).

Allaily,; Santoso, A.; Rofiq, M.; Sasongko, N.; Daulay, H.; Wiloso, E.; Widjaja, E.; Utomo, B.; Yanuar, A.; Suryani, S.; Erlambang, Y.; Thiyas, U.T.; 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 Journal of Environmental Science and Management, 10(3): 1275-1296 (**21 pages**).

Alan, H.; Köker, A.R., (2023). Analyzing and mapping agricultural waste recycling research: An integrative review for conceptual framework and future directions. Resour. Policy. 85: 103987 (**12 pages**).

El Ansari, L.; Chenoune, R.; Yigezu, Y.A.; Gary, C.; Belhouchette, H., (2020). Trade-offs between sustainability indicators in response to the production choices of different farm household types in drylands. Agronomy. 10(7): 998 (**24 pages**).

Arofi, F.; Rukmana, D.; Ibrahim, B., (2015). The analysis of integration sustainability of coffee plantation and goat husbandry (a case study in Ampelgading subdistrict, Malang regency, East Java, Indonesia. J. Econ. Sustainable Dev., 6(10): 1-9 (**9 pages**).

Asante, B.O.; Villano, R.A.; Patrick, I.W.; Battese, G.E., (2018). Determinants of farm diversification in integrated crop-livestock

farming systems in Ghana. Renewable Agric. Food Syst., 33(2): 131-149 (**19 pages**).

Aswanto, A.A.; Muhtarudin, M.; Farda, F.T.; Liman, L.; Tantalo, S., (2023). Potensi nutrien limbah kulit kopi untuk pakan ternak ruminansia di kecamatan Kebun Tebu kabupaten Lampung Barat. J. Res. Innovation Anim., 7(3): 306-311 (**6 pages**).

Ayalew, W.; Wu, X.-Y.; Tarekegn, G.M.; Chu, M.; Liang, C.-N.; Sisay Tessema, T.; Yan, P., (2023). Signatures of positive selection for local adaptation of African native cattle production: A review. J. Integr. Agric., 22(7): 1967-1984 (**18 pages**).

Azam, M.; Hunjra, A.I.; Bouri, E.; Tan, Y.; Saleh Al-Faryan, M.A., (2021). Impact of institutional quality on sustainable development: Evidence from developing countries. J. Environ. Manage., 298: 113465 (**15 pages**).

Bhatt, N.; Singh, N.P.; Mishra, A.K.; Kandpal, D.; Rajneesh; Jamwal, S., (2021). A detailed review of transportation stress in livestock and its management techniques. Int. J. Livest. Res., 11(1), 30-41 (**11 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. Int. J. Sustainable Dev. Plann., 18(10): 3181-3193 (**13 pages**).

Balaji, G.A.; Geethalakshmi, V.; Senthil, A.; Prahadeeswaran, M.; Iswarya, S.; Rajavel, M.; Bhuvaneswari, K.; Natarajan, B.; Senthilraja, K.; Gowtham, R.; Priyanka, S., (2023). Assessment of economic efficiency and its determents for mixed crop livestock production under dryland agriculture system in the western zone of Tamil Nadu, India. Sustainability. 15(10): 8332 (**22 pages**).

Bunmee, T.; Chaiwang, N.; Kaewkot, C.; Jaturasitha, S., (2018). Current situation and future prospects for beef production in Thailand - A review. Asian-Australas. J. Anim. Sci., 31(7): 968-975 (**8 pages**).

Brown, A.J.; Scoley, G.; O'Connell, N.; Gordon, A.; Lawther, K.; Huws, S.A.; Morrison, S., (2023). Pre-weaned calf rearing on Northern Irish dairy farms—Part 2: The impact of hygiene practice on bacterial levels in dairy calf rearing environments. Animals, 13(6): 1109 (**18 pages**).

Burrow, H., (2019). Strategies for increasing beef cattle production under dryland farming systems. Wartazoa. 29(4): 161-170 (**10 pages**).

Burrow, H.M., (2022). Overcoming major environmental and production challenges in cattle owned by smallholder farmers in the tropics. Caraka Tani: J. Sustainable Agric., 37(1): 161-170 (**10 pages**).

Chen, M.Z.; Xu, G.F.; Wei, M.J.; Li, X.W.; Wei, Y.Z; Diao, P.; Cui, P.; Teng, S., (2023). Optimization design and experiment on feeding and chopping device of silage maize harvester. Int. J. Agric. Biol. Eng., 16(3): 64-77 (**14 pages**).

Chia, S.Y.; Tanga, C.M.; van Loon, J.J.; Dicke, M., (2019). Insects for sustainable animal feed: Inclusive business models involving smallholder farmers. Curr. Opin. Environ. Sustainability. 41: 23-30 (**8 pages**).

Clark, M.A.; Domingo, N.G.G.; Colgan, K.; Thakrar, S.K.; Tilman, D.; Lynch, J.; Azevedo, I.L.; Hill, J.D., (2020). Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science. 370(6517): 705-708 (**4 pages**).

Coffey, D.; Dawson, K.; Ferket, P.; Connolly, A., (2016). Review of the feed industry from a historical perspective and implications for its future. J. Appl. Anim. Nutr., 4: 1-11 (**11 pages**).

Degila, J.; Sodedji, F.A.K.; Avakoudjo, H.G.G.; Tahi, S.P.G.; Houetohossou, S.C.A.; Honfoga, A.-C.; Tognisse, I.S.; Assogbadjo, A.E., (2023). Digital agriculture policies and strategies for innovations in the agri-food systems: Cases of five west African countries. Sustainability. 15(12): 9192 (**18 pages**).

Firman, A.; Nono, O.H., (2021). A social-ecological system approach to bali cattle raising in Timor island, Indonesia. Biodiversitas. 22(8): 3585-3593 (**9 pages**).

Gobena, M.M., (2017). Beef cattle production systems, marketing and constraints in Ethiopia. J. Mark. Consum. Res., 32: 1-7 (**7 pages**).

Grell, T.; Marchuk, S.; Williams, I.; McCabe, B.K.; Tait, S., (2023). Resource recovery for environmental management of dilute livestock manure using a solid-liquid separation approach. J. Environ. Manage., 325: 116254 (**10 pages**).

Habaora, F.; Fuah, A.M.; Abdullah, L.; Priyanto, R.; Yani, A.; Purwanto, B.P., (2019). Economic analysis of bali cattle farm in Timor island Indonesia. Int. J. Sci. Technol. Res., 8(10): 1576-1582 (**7 pages**).

Halimani, T.; Marandure, T.; Chikwanha, O.C,; Molotsi, A.H.; Abiodun, B.J.; Dzama, K.; Mapiye, C., (2021). Smallholder sheep farmers' perceived impact of water scarcity in the dry ecozones of South Africa: Determinants and response strategies. Clim. Risk Manage., 34: 100369 **(9 pages).**

Haryadi, F.T.; Widiati, R.; Kusumastuti, T.A.; Andarwati, S., (2019). Beef cattle farmers' group cohesion in Bantul and Sleman regencies Yogyakarta special region, Indonesia. J. Agric. Ext., 23(1): 223-229 (**7 pages**).

Kana Hau, D.; Nulik, J. (2021). Improving the supply of forage and staple food of smallholder farmers in therural marginal dry land of East Nusa Tenggara, Indonesia. E3S Web of Conference. 232: 02003 (**5 pages**).

Henn, D.; Duffy, C.; Humphreys, J.; Gibbons, J.; Byrne, K.A.; Styles, D., (2024). Cattle production strategies to deliver protein with less land and lower environment impact. J. Environ. Manage., 356: 120569 (**10 pages**).

Higgins, A.; Bruce, C.; McFallan, S.; Chilcott, C.; McKeown, A.; Williams, L.; Ackerman, J.; Wulandari, D.Y.; Dyer, R.; Le, N., (2023). Enhancing farmer linkages to markets in developing countries through mapping of supply chains and optimizing transport. Case Stud. Transp. Policy. 11: 100952 (**40 pages**).

Hutahaean, L.; Sirnawati, E.; Siti Rohaeni, E.; Bakrie, B., (2022). Duck business development strategy in duck farming center area of Indramayu regency, West Java province of Indonesia. E3S Web of Conference. 361: 01014 (**10 pages**).

Ibekwe, A.M.; Bhattacharjee, A.S.; Phan, D.; Ashworth, D.; Schmidt, M.P.; Murinda, S.E.; Obayiuwana, A.; Murry, M.A.; Schwartz, G.; Lundquist, T.; Ma, J.; Karathia, H.; Fanelli, B.; Hasan, N.A.; Yang, C.-H., (2023). Potential reservoirs of antimicrobial resistance in livestock waste and treated wastewater that can be disseminated to agricultural land. Sci. Total Environ., 872: 162194 (**25 pages**).

Ilham, N., (2015). Ketersediaan produk samping tanaman dan industri pertanian sebagai pakan ternak mendukung peningkatan produksi daging nasional. Forum Penelitian Agro Ekonomi, 33(1): 47-61 (**15 pages**).

Indrayani, I.; Andri, A.; Edwin, T., (2024). Farming sustainability of beef cattle in Pesisir Selatan, West Sumatera, Indonesia. Adv. Anim. Vet. Sci., 12 (3): 573-580 (**8 pages**).

Hermansyah; Israwati; Irawan, T.; Arsyelan, F.; Alexander, D.O., (2023). Penerapan strategi pemasaran, inovasi produk kreatif dan orientasi pasar untuk meningkatkan kinerja pemasaran umkm tekat tiga dara. J. Pengabdian Ibnu Sina. 2(1): 72-76 (**5 pages**).

Kapa, M.M.J.; Hasnudi.; Henuk, Y.L., (2019). Measuring technology sustainability status of local beef cattle under extensive rearing systems in the dryland area, Indonesia. IOP Conf. Ser.: Earth Environ. Sci., 260(1): 012018 (**5 pages**).

Koylal, J.A.; Kuang, S.M.; Abineno, J.C., (2022). Peranan dan kebijakan pendukung sektor peternakan sebagai leading sector dalam perekonomian Nusa Tenggara Timur. J. Agro Ekonomi., 40(1): 33–50 (**18 pages**).

Koyun, O.Y.; Balta, I.; Corcionivoschi, N.; Callaway, T.R., (2023). Disease

occurrence in-and the transferal of zoonotic agents by North American feedlot cattle. Foods. 12(4), 904 (**17 pages**).
Khoshnevisan, B.; Duan, N.; Tsapekos, P.; Awasthi, M.K.; Liu, Z.; Mohammadi, A.; Angelidaki, I.; Tsang, D.C.W.; Zhang, Z.; Pan, J.; Ma, L.; Aghbashlo, M.; Tabatabaei, M.; Liu, H., (2021). A critical review on livestock manure biorefinery technologies: Sustainability, challenges, and future perspectives. Renewable Sustainable Energy Rev., 135: 110033 (**24 pages**).
Kuralkar, P.; Kuralkar, S.V., (2021). Role of herbal products in animal production – An updated review. J. Ethnopharmacol., 278: 114246. (**11 pages**).
Lole, U.R.; Keban, A.; Sogen, J.G.; Mulyantini, N.G.A., (2021). Supply and value chain models in cattle marketing and its derivative products in East Nusa Tenggara province. Anim. Prod., 23(3): 197-208 (**12 pages**).
Mapiye, O.; Makombe, G.; Molotsi, A.; Dzama, K.; Mapiye, C., (2021). Towards a revolutionized agricultural extension system for the sustainability of smallholder livestock production in developing countries: The potential role of ICTs. Sustainability. 13(11): 5868 (**18 pages**).
Márton, J.; Szabó, F., (2023). Some actualities and challenges in sustainable beef cattle breeding and husbandry. Chem. Eng. Trans., 107: 241-246 (**6 pages**).
Mashur, M.; Bilad, M.R.; Kholik, K.; Munawaroh, M.; Cheok, Q.; Huda, N.; Kobun, R., (2022). The sustainability and development strategy of a cattle feed bank: A case study. Sustainability. 14(13): 7989 (**14 pages**).
McLeod, M.K.; Sufardi, S.; Harden, S., (2021). Soil fertility constraints and management to increase crop yields in the dryland farming systems of Aceh, Indonesia. Soil Res., 59(1): 68-82 (**15 pages**).
Meraner, M.; Finger, R., (2019). Risk perceptions, preferences and management strategies: Evidence from a case study using German livestock farmers. J. Risk Res., 22(1): 110-135 (**26 pages**).
Munasinghe, M., (2019). Sustainability in the twenty-first century : Applying sustainomics to implement the sustainable development goals. Sustainability in the Twenty-First Century: Applying Sustainomics to Implement the Sustainable Development Goals. 1-670 (**670 pages**).
Moustsen, V.A.; Seddon, Y.M.; Hansen, M.J., (2023). Animal board invited review: The need to consider emissions, economics and pig welfare in the transition from farrowing crates to pens with loose lactating sows. Animal. 17(9): 100913 (**12 pages**).
Morrone, S.; Dimauro, C.; Gambella, F.; Cappai, M.G., (2022). Industry 4.0 and precision livestock farming (PLF): An up to date overview across animal productions. Sensors. 22(12): 4319 (**25 pages**).
Mustapit; Subekti, S.; Sunartomo, A.F.; Rokhani, (2019). Achieving sustainable agriculture through enhancing agricultural extension institution. IOP Conference Series: Earth Environ. Sci., 250 (1): 012011 (**7 pages**).
Ngongo, Y.; Basuki, T.; Derosari, B.; Hosang, E.Y.; Nulik, J.; Dasilva, H.; Hau, D.K.; Sitorus, A.; Kotta, N.R.E.; Njurumana, G.N.; Pujiono, E.; Ishaq, L.; Simamora, A.V.; Mau, Y.S., (2022). Local wisdom of West Timorese farmers in land management. Sustainability. 14(10): 6023 (**21 pages**).
Odejobi, O.J.; Ajala, O.O.; Osuolale, F.N., (2024). Review on potential of using agricultural, municipal solid and industrial wastes as substrates for biogas production in Nigeria. Biomass Convers. Biorefin. 14(2): 1567-1579 (**13 pages**).
Osman, A.; Sbhatu, D.B.; Giday, M., (2020). Medicinal plants used to manage human and livestock ailments in Raya Kobo district of Amhara Regional State, Ethiopia. Evid Based Complement Alternat Med., 2020: 1329170 (**19 pages**).
Pampori, Z.A.; Sheikh, A.A., (2023). Technology driven livestock farming for food security and sustainability. Environ. Conserv. J., 24(4): 355-366 (**12 pages**).
Perdinan; Tjahjono, R.E.P.; Infrawan, D.Y.D.; Armanto, A.N.; Pratiwi, S.D.; Putra, E.I.; Yonvitner; Oktaviani, S.; Lestari, K.G.; Adi, R.F.; Sudiarno, A.R.; Kaban, E.; Widyaningrum, R.; Mayor, J., (2024). Management strategies of tropical savanna ecosystem for multiple benefits of community livelihoods in Semiarid region of indonesia. World Dev. Sustainability. 4: 100137 (**14 pages**).
Pighin, D.; Pazos, A.; Chamorro, V.; Paschetta, F.; Cunzolo, S.; Godoy, F.; Messina, V.; Pordomingo, A.; Grigioni, G., (2016). A contribution of beef to human health: A review of the role of the animal production systems. Sci. World J., 2016: 8681491 (**10 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**).
Ponnusamy, K.; Pachaiyappan, K., (2018). Strengthening extension research in animal husbandry: Review of issues and strategies. Indian J. Anim. Sci., 88(2): 137-143 (**7 pages**).
Pousga, S.; Magnusson, U.; Moumouni, I.; Dayo, G.-K.; Kante, A.; Boqvist, S., (2022). Extension services for livestock keepers in low-income countries—A low priority?. Animals. 12(6): 726 (**11 pages**).
Priyanto, R.; Riwukore, J.R.; Yani, A.; Purwanto, B.P.; Abdullah, L.; Fuah, A.M.; Habaora, F., (2020). Analysis of dynamic system toward governor policy of Nusa Tenggara Timur about quota of beef cattle export (Case study in plantation agroecosystem of Timor island). Annu. Res. Rev. Biol., 35(5): 32-41 (**10 pages**).
Qi, J.; Yang, H.; Wang, X.; Zhu, H.; Wang, Z.; Zhao, C.; Li, B.; Liu, Z., (2023). State-of-the-art on animal manure pollution control and resource utilization. J. Environ. Chem. Eng., 11(5): 110462 (**26 pages**).
Raharjo M.; Suroyo. (2013), Beef cattle integration on dry-land farming in sragen central-java indonesia: improvements of economic and environmental carrying capacity aspects. Anim. Prod., 15(2): 135-143 (**9 pages**).
Rahimi, J.; Fillol, E.; Mutua, J.Y.; Cinardi, G.; Robinson, T.P.; Notenbaert, A.M.O.; Ericksen, P.J.; Graham M.W.; Butterbach-Bahl, K., (2022). A shift from cattle to camel and goat farming can sustain milk production with lower inputs and emissions in north sub-Saharan Africa's drylands. Nat. Food. 3(7): 523-531 (**9 pages**).
Raisa, D.M.; Sirajuddin, S.N.; Abdullah, A., (2020). Analysis of farmers/livestock groups institutional characteristics in Barru regency. IOP Conference Series: Earth Environ. Sci., 492(1); 012163 (**8 pages**).
Randby, Å.T.; Bakken, A.K., (2021). Effect of acid based additive treatment of low dry matter grass crops on losses and silage quality in bunker silos. Anim. Feed Sci. Technol., 275: 114869 (**14 pages**).
Richards, D.; Yabar, H., (2023). Promoting energy and resource recovery from livestock waste: Case study Yuge farm, Japan. Case Stud. Chem. Environ. Eng., 7: 100299 (**9 pages**).
Riera, A.; Duluins, O.; Schuster, M.; Baret, P.V., (2023). Accounting for diversity while assessing sustainability: Insights from the Walloon bovine sectors. Agron. Sustainable Dev., 43(2): 30 (**20 pages**).
Rohaeni, E.S.; Ilham, N.; Saptati, R.A.; Rahayu, H.S.P.; Priyono; Anggraeny, Y.N.; Qomariah, R.; Pamungkas, D.; Ermuna, S.S.; Mahendri, I.G.A.P.; Mariyono; 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. Int. J. Sustainable Dev. Plann., 19(2): 481-500 (**20 pages**).
Rozaki, Z.; Wijaya, O.; Keothoumma, K.; Salim, E., (2020). A review: Farmers' local wisdom on natural resources. Andalasian Int. J. Agric. Nat. Sci., 1(01): 25-32 (**8 pages**).
Santoso, A.D.; Arianti, F.D.; Rohaeni, E.S.; Haryanto, B.; Pertiwi, M.D.; Panggabean, L.P.; Prabowo, A.; Sundari, S.; Wijayanti, S.P.; Djarot,

I.N.; Kurniawati, F.D.; Sahwan, F.L.; Prasetyo, T.; Barkah, A.; Adibroto, T.A.; Ridlo, R.; Febijanto, I.; Wasil, A.A.; Lusiana, S.; Rosmeika, R.; Heryanto, R.B., (2023). 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**).

Sathya, R.; Arasu, M.V.; Al-Dhabi, N.A.; Vijayaraghavan, P.; Ilavenil, S.; Rejiniemon, T.S., (2023). Towards sustainable wastewater treatment by biological methods – A challenges and advantages of recent technologies. Urban Clim., 47: 101378 (**18 pages**).

Sikone, H.Y.; Hartono, B.; Suyadi; Utami, H.D.; Nugroho, B.A., (2022). Value-added analysis of the meat agroindustry in indonesia. Online J. Anim. Feed Res., 12(5): 266-271 (**6 pages**).

Smol, M., (2023). Circular economy in wastewater treatment plant—Water, energy and raw materials recovery. Energies. 16(9): 3911 (**18 pages**).

Susanty, A.; Purwaningsih, R.; Santoso, H.; Arista, A.N.; Tjahjono, B., (2021). Measuring the sustainability of beef supply chain with rapid appraisal for beef supply chain. Vet. World, 14(9): 2488-2507 (**20 pages**).

Shubeena, S.; Bhattacharjee, S.; Raj, S., (2022). Scenario of livestock extension system, its organization and regulation. Guj. J. Ext. Edu., 33(1) (**8 pages**).

Stanley, Z.; Elin, R.; Lotta, R.;Ruben, H. (2023). Sustainibility assessment of economic, environmental and social impacts, feed-food competition and economic robustness of dairy and beef farming systems in south western europe. Sustainable Prod. Consumption (36) 439-448 **(10 pages).**

Tamsan, H.; Yusriadi, Y., (2022). Quality of agricultural extension on productivity of farmers: Human capital perspective. Uncertain Supply Chain Manage., 10(2): 625-636 (**12 pages**).

Terry, S.A.; Basarab, J.A.; Guan, L.L.; McAllister, T.A., (2021). Strategies to improve the efficiency of beef cattle production. Can. J. Anim. Sci., 101(1): 1–19 (**19 pages**).

Tiro, B.M.W.; Beding, P.A.; Suprihadi, K.; Ondikeleuw, M.; Usman; Subiharta; Hayati R.N.; Hanifah, V.W., (2023). Utilization of rice straws as feed for beef cattle during the dry season in Merauke regency, South Papua, Indonesia. Nongye Jixie Xuebao Transactions of the Chinese Society of Agricultural Machinery. 54(9): 72-80 (**9 pages**).

Tulu, D.; Gadissa, S.; Hundessa, F.; Kebede, E., (2023). Contribution of climate-smart forage and fodder production for sustainable livestock production and environment: Lesson and challenges from ethiopia. Adv. Agric., 2023: 8067776 (**11 pages**).

Uddin, M.E.; Kebreab, E., (2020). Review: Impact of food and climate change on pastoral industries. Front. Sustainable Food Syst., 4: 543403 (**13 pages**).

Vaishnav, S.; Saini, T.; Chauhan, A.; Gaur, G.K.; Tiwari, R.; Dutt, T.; Tarafdar, A., (2023). Livestock and poultry farm wastewater treatment and its valorization for generating value-added products: Recent updates and way forward. Bioresour. Technol., 382: 129170 (**11 pages**).

Vechi, N.T.; Mellqvist, J.; Scheutz, C., (2022). Quantification of methane emissions from cattle farms, using the tracer gas dispersion method. Agric. Ecosyst. Environ., 330: 107885 (**11 pages**).

Wegari, D.; Gelata, F.T., (2021). Analysis of beef cattle value chain and value addition activities: Empirical evidence from Toke Kutaye and Bako Tibe districts, West Shewa zone, Oromia national regional state, Ethiopia. Sarhad J. Agric., 37(2): 377-385 (**9 pages**).

Widjaja, E.; Utomo, B.N.; Santoso, A.D.; Erlambang, Y.P.; Surono; Frimansyah, 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., (2024). Sustainability index analysis for environmentally low-input integrated farming. Global J. Environ. Sci. Manage., 10(2): 537-556 (**20 pages**).

Widyas, N.; Widi, T.S.M.; Prastowo, S.; Sumantri, I.; Hayes, B.J.; Burrow, H.M., (2022). Promoting sustainable utilization and genetic improvement of indonesian local beef cattle breeds: A review. Agriculture. 12(10): 1566 (**25 pages**).

Zhang, M.; Wang, X.; Feng, H.; Huang, Q; Xiao, X.; Zhang, X., (2021). Wearable internet of things enabled precision livestock farming in smart farms: A review of technical solutions for precise perception, biocompatibility, and sustainability monitoring. J. Cleaner Prod., 312: 127712 **(19 pages).**

Zaied, A.J.; Geli, H.M.E.; Cibils, A.F.; Sawalhah, M.N.; Holechek, J.L.; Gard, C.C.; Idhirij, S.A.; Gedefaw, M.G.; Torell, G.L., (2021). Beef cattle price and production patterns in relation to drought in New Mexico. Sustainability. 13(18): 420 (**20 pages**).

AUTHOR (S) BIOSKETCHES

Simamora, T., Ph.D., Lecturer, [1]Animal Husbandry Study Program, Faculty of Agriculture, Science and Health, Timor University; Post Doctoral, [2]Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
• Email: *turesimamora@unimor.ac.id*
• ORCID: 0000-0001-8331-5590
• Web of Science Researcher ID: JGL-8414-2023
• Scopus Author ID: 58209128900
• Homepage: https://www.unimor.ac.id/

Rofiq, M.N., Ph.D**.,** Researcher, Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
• Email: *mnas001@brin.go.id*
• ORCID: 0000-0002-4632-9376
• Web of Science Researcher ID: AAZ-6409-2020
• Scopus Author ID: 57221967761
• Homepage: https://brin.go.id/

Hutahaean, L., M.S., Senior Researcher, Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
• Email: *lint001@brin.go.id*
• ORCID: 0000-0002-8437-5605
• Web of Science Researcher ID: NA
• Scopus Author ID:57225173715
• Homepage: https://brin.go.id/

AUTHOR (S) BIOSKETCHES

Sio, S., Ph.D., Lecturer, Animal Husbandry Study Program, Faculty of Agriculture, Science and Health, Timor University.
• Email: *stefsio67@gmail.com*
• ORCID: 0000-0002-3287-6328
• Web of Science Researcher ID: NA
• Scopus Author ID: 57506571400
• Homepage: https://www.unimor.ac.id/

Hutapea, R., M.Eng., Senior Researcher, Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
• Email: *ramo001@brin.go.id*
• ORCID: 0009-0001-0572-8071
• Web of Science Researcher ID: HSA-6979-2023
• Scopus Author ID: 58717129100
• Homepage: https://brin.go.id/

Irawan, D., M.Sc., Researcher at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
• Email: *dody001@brin.go.id*
• ORCID: 0000-0003-1948-4415
• Web of Science Researcher ID: HRA-9467-2023
• Scopus Author ID: NA
• Homepage: https://brin.go.id/

Suryani, S.Si., Researcher, Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
• Email : *sury021@brin.go.id*
• ORCID: 0009-0005-6072-8911
• Web of Science Researcher ID: JXN-4818-2024
• Scopus Author ID: NA
• Homepage: https://brin.go.id/

Diastuti, R., M.Si**.,** Senior Researcher, Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
• Email: *renn003@brin.go.id*
• ORCID: 0009-0000-6874-8195
• Web of Science Researcher ID: NA
• Scopus Author ID: NA
• Homepage: https://brin.go.id/

Thiyas, U.N, S.Si**,** Researcher at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.
• Email: *ulfa002@brin.go.id*
• ORCID: 0009-0003-8517-9838
• Web of Science Researcher ID: JXN-6131-2024
• Scopus Author ID: -
• Homepage: https://brin.go.id/

Correia, B.A, Ph.D., Department of Agricultural, Faculty of Agriculture, Timor Lorosa'e National University, Dili, Democratic Republic of Timor-Leste.
• Email: *brigida.correia64@gmail.com*
• ORCID: 0009-0002-0500-3043
• Web of Science Researcher ID: NA
• Scopus Author ID: NA
• Homepage: https://untl.edu.tl/pt/

Correia, L.T, Ph.D., Department of Agricultural, Faculty of Agriculture, Timor Lorosa'e National University, Dili, Democratic Republic of Timor-Leste.
• Email: *correia.ligia3@gmail.com*
• ORCID: 0009-0008-3406-1991
• Web of Science Researcher ID: NA
• Scopus Author ID: NA
• Homepage: https://untl.edu.tl/pt/

HOW TO CITE THIS ARTICLE

Simamora, T.; Rofiq, M.N.; Hutahaean, L.; Sio, S.; Hutapea, R; Irawan, D.; Suryani.; Diastuti, R.; Thiyas U.N.; Coreia B.A.; Correia L.T. (2024). Sustainability index for eco-friendly cattle farming in dry climate regions. Global J. Environ. Sci. Manage., 10(SI): 279-302.

DOI: 10.22034/gjesm.2024.10.SI.18

URL: https://www.gjesm.net/article_715766.html

Global J. Environ. Sci. Manage. 10(SI): 303-322, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

CASE STUDY

Spatial planning strategies and community behavior towards flood control

R. Dani[1], Sujianto[2,*], Nofrizal[3], B. Amin[3]

[1] *Environmental Science Program, Riau University, Bina Widya, Simpang Baru, Tampan District, Pekanbaru City, Riau Province, Indonesia*

[2] *Faculty of Social and Political Science, Riau University, Bina Widya, Simpang Baru, Tampan District, Pekanbaru City, Riau Province, Indonesia*

[3] *Faculty of Fisheries and Marine, Riau University, Bina Widya, Simpang Baru, Tampan District, Pekanbaru City, Riau Province, Indonesia*

ARTICLE INFO

Article History:
Received 18 April 2024
Revised 24 June 2024
Accepted 28 August 2024

Keywords:
Behavior
Flood
Spatial planning strategy
Waste management
Water use

ABSTRACT

BACKGROUND AND OBJECTIVES: The flooding phenomenon in Pekanbaru City is an interrelated problem between socio-economic and environmental problems. A significant socio-economic issue contributing to annual flooding in Pekanbaru City is the management of waste. Additionally, the patterns of water usage among the population represent another socio-economic challenge. This oversight represents a significant weakness in flood mitigation strategies, as those most vulnerable to flooding are frequently the ones whose needs are neglected in the planning process. Prioritizing socio-economic factors as a fundamental principle is essential for effective flood management and disaster response. The aim of this study is to develop spatial planning strategies and community behavior towards flood control in the Sail Watershed, Pekanbaru City. The innovation presented in this study lies in its unique integration of the spatial aspects of urban flooding phenomena with the behavioral patterns of communities, an area that has not been addressed in earlier research. Previous investigations primarily emphasized the development of physical interventions to alleviate the effects of flooding disasters.

METHODS: The study utilizes participatory prospective analysis to investigate the strategies of spatial planning and the behaviors of communities in relation to flood control measures. Prospective analysis in this study was used to determine the dominant variables that influence strategy determination. The prospective method is a tool used for policy analysis, especially in study involving sustainable development, because it can facilitate the anticipation of change in an unstable environment.

FINDINGS: The results of the study show that minimizing flood disasters can be done through structural development and synergized with non-structural development that provides space for community behavior so that the results are more optimal. The management of flood control is executed in a comprehensive and integrated fashion, which begins with the coordination of stakeholders and extends to the management of flood disasters, flood response, and community involvement. Key strategies for effective flood control involve the collaboration of technical stakeholders, the governance of floodplains, the application of flood mitigation strategies, and the engagement of local communities.

CONCLUSION: The findings of this study indicate that coordination emerges as the most significant variable, exhibiting a direct influence weight of 3750 and an indirect influence weight of 3597. Subsequently, the variables of management, mitigation, and involvement are ranked in order of their influence. The implementation of spatial planning strategies and community engagement in flood control necessitates the collaboration of technical stakeholders involved in flood management. This comprehensive approach encompasses activities before, during, and after a flood event. Effective floodplain management entails the identification of flood boundaries, the establishment of zoning regulations, ongoing supervision and monitoring, as well as the active participation of the community.

DOI: 10.22034/gjesm.2024.10.SI.19

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
7

NUMBER OF TABLES
6

*Corresponding Author:
Email: *sujianto0926@gmail.com*
Phone: +62761 63266
ORCID: 0009-0008-5398-5196

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the “Show Article”.

INTRODUCTION

Flooding can occur due to a multitude of factors, including the flow of rivers, runoff from precipitation, and coastal phenomena. These coastal dynamics encompass storm surges, wave activity, tidal movements, wind influences, and variations in atmospheric pressure (Mei *et al.,* 2024). Types of floods include those caused by heavy rainfall, continuous rainfall, and melting snow, depending on the catchment area type (Fischer and Schumann, 2024). In numerous regions, the runoff of water and traffic congestion significantly contribute to flooding incidents, and there exists a negative correlation between the frequency of flood events and the level of community preparedness (Kittipongvises *et al.*, 2020). The risks associated with these different flood processes are influenced by their frequency, severity, exposure levels, vulnerability to damage, and the effectiveness of mitigation measures (Coombes, 2023). Floods are considered one of the most catastrophic natural disasters on a global scale (Narendra *et al.,* 2024). In recent years, the frequency of flood disasters has been on the rise (Turkington *et al.*, 2016). Such incidents markedly disturb regional functions, causing traffic bottlenecks, ecological damage, and the unfortunate possibility of casualties and property destruction (Yan *et al.*, 2024). The impacts of flooding are far-reaching, affecting various aspects of society, including the economy, infrastructure, and daily life (Srivanit *et al.,* 2024). Statistics show that global losses from flood disasters account for 20 percent (%) of all natural disaster-related losses (Zhou *et al.*, 2019). Since the beginning of the 21st century, it has been estimated that global flood-related losses have reached approximately USD 651 billion, while the percentage of the population at risk of flooding has risen by nearly 24% (Yang *et al.*, 2024). Floods can be triggered by natural events, human activities, or a combination of both, and have the potential to cause fatal injuries, displace large populations, and damage the environment (Buisan *et al.,* 2019). Flooding is influenced by a combination of factors, including alterations in precipitation patterns, increasing sea levels, climate change, and the effects of urban development.(Malalgoda *et al.*, 2016). These factors are key contributors to the increased risk of flood disasters (Li *et al.*, 2024), leading to alterations in river flows and a decrease in water availability (Qi *et al.,* 2024). Consequently, water storage capacity and drainage efficiency are reduced, heightening vulnerability to flood disasters (Jin *et al.,* 2024). The phenomenon of global climate change is an indisputable fact, anticipated to intensify the hydrological cycle, which will result in an increase in the frequency, intensity, and duration of extreme rainfall events (Qi *et al.*, 2022). As a global concern, climate change exacerbates the hydrological cycle by causing uneven rainfall distribution, which leads to extreme rainfall in many regions (Allegri *et al.*, 2024). The occurrence of intense rainfall significantly increases the likelihood of flooding in metropolitan regions. Conversely, urbanization plays a vital role in driving substantial changes in the physical landscape and land utilization practices within cities. (Pour *et al.*, 2020). Population growth necessitates considerable alterations in land use and contributes to deforestation, thereby facilitating a movement from natural landscapes to more developed environments (Ibrahim *et al.*, 2021). This alteration affects the water cycle and rainfall patterns (Zhang and Huang, 2024). Changes in land cover have disrupted the natural water cycle by reducing water resources (Hallegatte *et al.*, 2013). From a hydrological standpoint, the proliferation of urban areas has modified the characteristics of runoff and peak flow, resulting in an increased vulnerability to flooding events (Chen *et al.*, 2015). Urbanization also plays a significant role in the rise of flood events (Butler *et al.*, 2016). Various socio-economic determinants play a vital role in contributing to the incidence of flooding (Zhu *et al.,* 2023). Trash can exacerbate urban flooding by clogging drainage systems and increasing waterlogging (Lin *et al.*, 2022). Ineffective waste management heightens the risk of flooding (Simonovic and Carson, 2003). Flooding can significantly affect the vulnerability of communities by altering various determinants, including economic conditions, educational opportunities, social connections, and overall physical well-being (Arvin *et al.,* 2023). During floods, socially vulnerable individuals suffer more severe consequences compared to those who are more privileged (Rouhanizadeh and Safapour, 2023), reducing their chances of recovery and raising the risk of death (Rouhanizadeh, 2020). Such inequalities weaken the community's overall resilience. Urban flood

resilience is defined as a city's capability to resist flooding, recover from both physical harm and socioeconomic upheaval, sustain its identity, and evolve in response to future flood challenges (Mehryar and Surminski, 2022). This idea functions as an effective method for averting and diminishing the consequences of flooding that cities currently experience (Forrest *et al*., 2020). Flood mitigation strategies are essential for addressing the growing issue of flood events (Qi *et al*., 2022). Eco-friendly mitigation measures, such as green roofs, rain gardens, and permeable pavements, play a crucial role in managing stormwater through ecological services (Ahiablame and Shakya, 2016). The implementation of these sustainable strategies occurs through the integration of landscape ecological design and engineering technologies, aimed at addressing a range of urban water issues, such as the management of flood risks (Liang *et al*., 2019). Implementing flood mitigation measures is vital for enhancing urban resilience and disaster mitigation capabilities. This not only helps minimize losses from flood disasters but also leverages the unique benefits of different flood mitigation strategies (Wan *et al.,* 2024). Flood mitigation has become a critical topic in global disaster control and management (Chen *et al*., 2021). Extensive research on urban flood risk has led to the development of various methods. The dependability of models employed in the formulation of flood mitigation strategies is still insufficient. Frequently, strategies for disaster mitigation are executed without a comprehensive evaluation of the interplay among various flood mitigation techniques, the specific characteristics of flooding, and the overarching objectives of disaster mitigation. This situation leads to two main issues. First, the chosen flood mitigation measures for a particular area may not meet construction requirements. For instance, installing permeable pavement on a heavily trafficked road can significantly reduce the road's lifespan. Furthermore, the implemented flood mitigation measures might not sufficiently cater to the demands for reducing the impact of flood disasters (Liu *et al*., 2014). Limitations of construction sites are a key factor in choosing appropriate flood mitigation measures. Numerous nations that are experiencing increased flood risks are seeking to adopt measures aimed at improving the flood resilience of their urban areas. The spatial planning of drainage systems can serve as a central element in these efforts. The implementation of open space systems provides a sustainable and resilient method for tackling drainage problems, as they offer storage capacity designed to foresee and reduce the risks associated with flooding. Furthermore, river restoration initiatives can contribute to flood storage capacity and help link environmentally significant areas or planned parks, supporting the development of multifunctional urban open space systems. Enhancing information systems is a crucial strategy during a flood disaster (Luo *et al.,* 2024). Well-designed information systems can mitigate stress, enhance social unity among communities affected by natural disasters, and supply vital information that is crucial for the management of such disasters (Aisha *et al.,* 2015). During a crisis, it's vital for people to access information to understand what others are experiencing (Wang *et al.,* 2024). Additionally, such information offers guidance on how to stay safe during the disaster (Talabi *et al*., 2022). The role of social media in orchestrating flood response activities is significant, as it aids in mitigating feelings of loneliness and isolation experienced by those impacted (Sharp and Carter, 2020). In summary, social media platforms facilitate the dissemination of emergency messages related to floods (Hazzam, 2022). Flood control policies can serve as a strategy for managing flood disasters (Munoz *et al.,* 2024). These policies frequently depend on infrastructure elements, including dams, the restoration of vegetation, or the conversion of regions characterized by rapid drainage into areas designed to retain or moderate water flow. Dams, for instance, can store excess water during heavy rainfall, reducing downstream flooding and providing benefits like a reliable water supply (Boulange *et al*., 2021). Nonetheless, the construction of dams can result in negative ecological and social consequences, and their potential failure may cause even more significant harm (Brown *et al*., 2009). Conversely, nature-based solutions have proven effective at reducing peak discharge in small to moderate floods but are less effective in large floods (Bathurst *et al*., 2016). As a result, experts advocate for a combination of various flood management techniques to formulate resilient and sustainable solutions, yet pinpointing the

appropriate blend remains a complex task (Genovese and Thaler, 2020). Indonesia is known for being frequently affected by natural disasters (Kurniawan *et al.,* 2022). Besides earthquakes, flooding represents a prevalent natural disaster within the country, particularly during the rainy season that spans from October to April, coinciding with the west monsoon winds originating from the Pacific Ocean (Texier-Teixeira and Edelblutte, 2017). Flooding is the most frequent and dynamic disaster threat in Indonesia (Nasution et al., 2022). One of the provinces that has experienced significant flooding is Riau Province, which faces flood risks impacting 6,009,366 people socially, causing physical damages worth USD 684 million, economic losses amounting to USD 2 billion, and environmental damage over 726,422 hectares (ha) (NADC, 2022). Pekanbaru City, located in Riau Province, experiences frequent flooding each year. The flood-affected area in Pekanbaru City covers 291 hectares, impacting 353,133 residents and causing economic losses of USD 33 million. The city's flood disaster risk index is categorized as high, with a score of 36.00 (NADC, 2022). There are at least 113 inundation points and 375 flood-related issues that need to be addressed (PCPWSPD, 2020). In Pekanbaru City, several roads are compromised by standing water, leading to interruptions in residents' daily lives and posing challenges to the economic vitality of the region (Susilo, 2019). Problems with the urban drainage system lead to overflowing drainage channels, resulting in flooding and environmental damage (Owolabi et al., 2022). The areas most impacted by flooding in Pekanbaru City are those within the Sail Watershed. The Sail Watershed is integral to the urban development of Pekanbaru City, encompassing approximately one-third of the city's territory located south of the Siak River, which contributes to the drainage of the watershed (PCPWSPD, 2020). Approximately 327 thousand people, or 33.27% of Pekanbaru City's total population, live in sub-districts along the Sail River (SPM, 2022). The Sail Watershed, located in the southern part of Pekanbaru City, is a priority area for flood management efforts (Putra *et al.,* 2016). The flooding issue in Pekanbaru City is closely linked to social, economic, and environmental challenges. In the context of the Strategic Environmental Study for the Pekanbaru City Spatial Plan covering the period from 2020 to 2040, an assessment of sustainable development issues has been conducted, highlighting that three out of five prioritized issues are linked to the city's flooding challenges. These include the decline in groundwater availability and river quality, the suboptimal drainage system for flood and waterlogging control, and reduced water infiltration in the area. Another significant factor contributing to floods is socio-economic conditions. Poor waste management, where residents carelessly dispose of garbage into rivers, obstructs the flow and leads to flooding in Pekanbaru City (Suryani and Ningsih, 2019). The waste management system remains dependent on the local government, which continues to use an outdated method of transporting waste directly to the final processing site in Muara Fajar. Furthermore, the routine utilization of water for various activities such as bathing, laundering, and other domestic purposes plays a significant role in the socio-economic dynamics that lead to flooding. Research on urban flood resilience has gained increasing importance over recent decades, with various methods developed to evaluate it. Various studies propose that the resilience of urban areas can be strengthened at every stage of flood management, encompassing the periods before, during, and after flooding incidents. This approach underscores that enhancing resilience should encompass the entire flood management process (Zhu *et al.,* 2021), including prevention and preparedness before the flood, response during the flood, and recovery and mitigation afterward. However, current flood disaster mitigation efforts often overlook socio-economic factors. This oversight highlights a critical flaw in flood mitigation strategies, as the individuals most at risk of flooding often have their needs overlooked during the planning stages (Moller-Jensen *et al.* 2023). Addressing these gaps, it is crucial that effective flood management and disaster response prioritize socio-economic considerations as a fundamental principle (Winsemius *et al.,* 2018). This requires a strong commitment to addressing the diverse needs and capabilities of all societal levels (Chakraborty *et al.,* 2023). It is imperative to address the aspect of role division when examining community participation in spatial planning aimed at flood mitigation. Often the community becomes apathetic because of the unequal role division where they are

limited by the government (Hibbard and Lurie, 2000). Therefore, appropriate spatial planning involving the important role of the community is the reason for conducting a study of the influence of spatial planning and community behavior on Flood Control in the Sail Watershed, Pekanbaru City. The study introduces a novel approach by integrating the spatial dynamics of urban flooding phenomena with community behavior, an area that has not been previously explored. Prior studies predominantly concentrated on implementing physical flood control measures aimed at mitigating the effects of such disasters. The study uses a modified participatory prospective analysis (PPA) with a geographic information system for the analysis of flood control strategies. By taking a holistic approach that accommodates community needs, flood disaster mitigation strategies can be truly effective. The aim of this study is to develop spatial planning strategies and community behavior towards flood control in the Sail Watershed, Pekanbaru City. The development of flood control strategies was informed by an examination of the social characteristics inherent within society. The study was carried out in the Sail Watershed area, including Tanjung Rhu Village and Sekip Village (Limapuluh District), Tangkerang Utara Village, Simpang Tiga Village, and Tangkerang Labuai Village (Bukit Raya District), Sukamaju Village and Sukamulia Village (Sail District), Bambu Kuning Village, Sialang Sakti Village, East Tangkerang Village, and Rejosari Village (Tenayan Raya District), Pematang Kapau Village, Pebatuan Village, and Sialang Rampai Village (Kulim District), Indonesia in 2022 to 2023.

MATERIALS AND METHODS

This study adopts a mixed-methods research design, which combines qualitative and quantitative approaches. A mixed-methods study is characterized by the simultaneous use of both qualitative and quantitative methods to address research questions within a unified framework. Mixed method relates to the use of more than one method in a research that uses both qualitative and quantitative. Qualitative and quantitative are used as empirical evidence in answering research problems in order to obtain complete findings. The use of this method is seen as providing a more complete understanding of the study problem. The complexity of this approach surpasses the straightforward collection and analysis of two data types; it integrates the functionalities of both research methodologies, resulting in a cumulative strength that exceeds that of qualitative and quantitative research conducted independently. Mixed methods study is also referred as a methodology that provides philosophical assumptions in showing direction or providing instructions on how to collect data and analyze data as well as a combination of quantitative and qualitative approaches (Sarwono, 2011). Due to restrictions in time and financial resources, this research relied on samples for its analysis. A sample serves as a segment of the overall population. The sampling method implemented in this study is categorized as a non-probability sampling technique, with a focus on purposive sampling procedures. Purposive sampling is employed by researchers due to the existence of specific criteria that guide the selection of individuals for the sample. This technique of sampling is characterized by deliberate considerations that inform the selection process. Certain considerations are made to respondents who already have criteria in the study. Sampling carried out in this study was by using the Isaac and Michael formula (Sugiyono, 2017). Thus, the number of respondents for this research questionnaire was 225 people representing heads of families. Purposive sampling is employed by researchers due to the existence of specific criteria that guide the selection of individuals for the sample. This technique of sampling is characterized by deliberate considerations that inform the selection process. The Mixed Method in this study was carried out using PPA analysis techniques. This analysis aims to determine the dominant variables that influence strategy determination. This technique is a tool designed to find out or investigate and anticipate changes with the participation of experts or stakeholders. In the realm of policy analysis, prospective analysis is an essential methodology, particularly relevant to sustainable development studies, as it aids in predicting shifts within volatile contexts. Matrice d'impacts croises-multiplication application´ or commonly known as micmac analysis is used to evaluate a program and find key variables that can be used to improve in the future. Micmac results can provide forecasting output from variable priorities. Micmac is believed to be able to find which

parts are problematic in a system. The culmination of the PPA analysis is a graphical representation organized into quadrants, which elucidates the placement of all variables, identifying them as either output, input, or stakes variables, and detailing the nature of their interrelationships, indicating whether these connections are strong or weak. The second output is the same as the first output but is expressed in the future or projection. The third output, variable priorities are raised so that the system being evaluated runs well. The fourth output is identical to the third output, yet it represents a forecast for the future. This will assist in equipping policies to anticipate changes from the beginning. Micmac's forecasting is done by repeating/iterating and analyzing nearby shifts. To determine key or dominant factors, the MICMAC software prospective analysis program is used to show a graph of the level of influence and dependency between factors in the system (Damai *et al.,* 2011).

PPA consists of four quadrants, they are (Fig. 1):

1. First quadrant (Access/supply)

This quadrant encompasses elements that exert a significant influence while exhibiting a relatively weaker dependence. Factors in this quadrant are determining or driving factors (Driving variables) which are included in the category of the strongest factors and key factors in the system.

2. Second quadrant (Stakes/relay)

This quadrant encompasses elements that exert a significant influence while also exhibiting a high degree of dependence. The factors located within this quadrant are considered robust variables or levers, which play a crucial role as key components within the system.

3. Third quadrant (Output)

This quadrant contains factors that have a weak influence and a very strong dependence. Factors in this quadrant are output factors (Output variables) and are not key factors in the system.

4. Fourth quadrant (Autonomos)

This quadrant encompasses elements that exhibit a minimal influence and demonstrate weak interdependence. The factors situated within this quadrant are considered to be of limited significance, often referred to as marginal variables.

RESULTS AND DISCUSSION

Behavioral characteristics of waste management and water utilization in the Sail Watershed, Pekanbaru City

Waste management behavior

The waste management system still depends on local governments, relying on the old system called transporting waste directly to the final processing site.

Table 1 shows that from 225 respondents, it was found that 189 respondents or 84% disposed of waste at Temporary Disposal Site and Final Processing Site. Generally, waste is transported by waste officers from house to house to be taken to the Temporary Disposal Site, and the public pays a waste fee to the waste manager in the range of USD 0.64 to 2.23 per month. Concurrently, 36 individuals chose not to deposit their refuse at the Temporary Disposal Site. This decision stems from the fact that

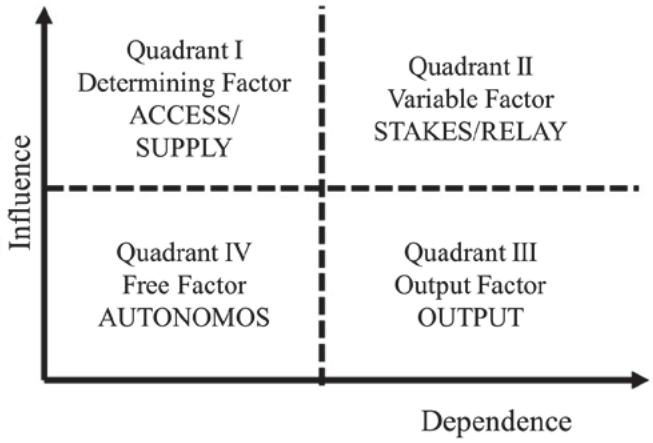


Fig. 1: Participatory prospective analysis quadrant

Table 1: Waste processing behavior in the Sail Watershed Pekanbaru City

Waste management behavior	Total		(%)	
	Yes	No.	Yes	No.
Recycle	27	198	12	88
Compost/fertilizer	37	188	16.4	83.6
Transported by officers/disposed of to temporary disposal site/final processing site	189	36	84	16
Sold/given to others	137	88	60.9	39.1
Animal food	84	141	37.3	62.7
Buried	22	203	9.8	90.2
Burnt	129	96	57.3	42.7
Thrown in to the river/gutter	9	216	4	96

Table 2: Treatment of used goods

Treatment of used goods	Total		%	
	Yes	No.	Yes	No.
Used for other purposes	197	28	87.6	12.4
Given to others	202	23	89.8	10.2
For sale	161	64	71.6	28.4
Discarded	164	61	72.9	27.1

their community lacks a designated Temporary Disposal Site and is not supported by waste collection services. Furthermore, waste sorting behavior is carried out for easily decomposable/organic and inorganic waste. It was discovered that 155 respondents or 68.8% of people's behavior in waste sorting sorted easily decomposable/organic and inorganic waste, and 70 re-spondents or 31.2% did not separate easily decomposable/organic and inorganic waste. The process of waste sorting encompasses both biodegradable/organic materials and inorganic waste. Implementing effective waste sorting practices can yield beneficial outcomes for the environment, enhance public health, and contribute positively to the global economy (Cheon *et al*., 2024). Environmental awareness can motivate individuals to sort and recycle waste. External factors, including the physical and social environmental conditions of a community, play a significant role in influencing individuals' waste sorting behaviors. Therefore, it is essential to reinforce policies, provide appropriate facilities, and engage the community in promoting behavioral change (Cao *et al*., 2024). The motivations behind the choice to bring personal shopping bags are multifaceted. Many individuals find this practice to be more convenient and straightforward, as it alleviates the need to handle numerous plastic bags. Additionally, there is a growing awareness of the importance of waste reduction, which further encourages this behavior. An additional factor contributing to this phenomenon is the adoption of paid plastic initiatives in various shopping centers. This approach emphasizes the importance of reusing materials by evaluating items prior to disposal and assessing their potential for reuse.

As depicted in Table 2, the community engages in the practice of waste reuse by transforming plastic mineral water bottles into drinking bottles and/or storage units for cleaning fluids. Donating used clothing that is still wearable is a viable option, as well as offering other items like books and furniture that have been substituted due to boredom or slight imperfections. This practice not only helps to decrease waste but also serves to benefit individuals who may find these items useful. The community is transforming waste by utilizing plastic mineral water bottles as vessels for drinking or for the storage of cleaning agents. It is crucial to raise public awareness regarding environmental issues, especially in the context of household waste management and water conservation, to ensure a sustainable future (Ibrahim *et al*., 2021).

Water use behavior

The availability of water plays a crucial role in maintaining the stability of water supply, particularly in recharge areas. At present, the inhabitants of Pekanbaru City primarily rely on well water to fulfill

Table 3: Water use behavior when washing

Description	Category	Frequency	(%)
At home, let the water run unused	Never	93	41.3
	Sometimes	125	55.6
	Always	7	3.1
	Total	225	100,0
Use of water is to washing utensils	Collected water	80	35.6
	Flowing water	145	64.4
	Total	225	100
Use of water is to wash vegetables and fruits	Collected water	75	33.3
	Flowing water	150	66.7
	Total	225	100
Use of water to rinse laundry	Collected water (<= 2 rinses)	98	43.6
	Collected water (> 2 rinses)	85	37.8
	Flowing water	42	18.7
	Total	225	100

their requirements for clean water. A total of 218 respondents used clean water sources from drilled wells and dug wells or 96.9%. In meeting water needs, 149 households (66.2%) received water from one source, 69 households (30.7%) received water from two sources. The expansion of the population will result in persistent groundwater withdrawal, potentially leading to land subsidence. This land subsidence, in turn, elevates the risk of flooding occurrences (Zhang and Huang, 2024).

Analysis of the data indicates that the predominant method of washing among respondents involved the use of flowing water. In particular, 145 individuals, or 64.4% of the sample, utilized flowing water for washing utensils, whereas 150 individuals, equating to 66.7%, applied this method when washing clothes. The practice of utilizing recycled water remains relatively uncommon among the general populace. Within the study area, merely 5 households, representing 2.2% of respondents, reported the use of recycled water (Table 3). Using flowing water is more wasteful than using collected water because when using flowing water, it is difficult to control the amount of water used, some taps with flowing water are designed without considering efficiency and the inability to stop the flow of water easily and causes unnecessary water waste. However, in terms of water use when washing clothes, there have been efforts to use collected water. The utilization of collected water in designated receptacles, such as buckets or basins, facilitates more effective management of water consumption. Some behaviors are notably more effective in conserving water, such as ensuring that the tap is turned off when it is not in operation and utilizing faucets designed with water-saving features. Water that has been previously utilized is commonly applied in the washing of rice, vegetables, and fruits, in addition to being used for the irrigation of plants. Conversely, water designated for ablution and laundry purposes is allocated for the sanitation of bathroom areas. Water conservation efforts from the use of used water can contribute to sustainable water resource management. Individuals' approaches to water conservation are largely shaped by their behaviors and social norms, while established habits serve as a key factor influencing their water-saving actions (Russell and Knoeri, 2020). So, changing people's habits is an important component in managing water demand in cities. People living in villages are more concerned about saving water use than those in cities (Njoku *et al*., 2022). Influential elements encompass family educational approaches, insufficient access to domestic water supplies, and the societal emphasis on the value of clean water. Furthermore, this research suggests the establishment of a grey water treatment system aimed at decreasing overall water usage and promoting the reuse of water resources.

High rainfall intensity frequently leads to flooding, primarily due to the diminished capacity of water catchment areas. Enhancing the availability of catchments and bio pores is a crucial approach to addressing flood challenges, with bio pore availability currently at 43.1%. The presence of bio pores can increase water absorption into the soil to reduce flooding and improve the quality of the soil

around where the bio pores are installed. Moreover, it has been observed that 198 households, or 88% of the total, possess plants in their yards. The rationale behind this trend lies in the water absorption capabilities of plants; a greater presence of vegetation correlates with improved water absorption in the soil, which serves to mitigate flooding.

Spatial planning strategy and community behavior to control floods in the Sail Watershed, Pekanbaru City

Identify variables' status

The first interpretation of the results is to identify variables. The variables in micmac are divided into four, called the access variable (supply) in quadrant I, stakes (relay) in quadrant II, output in quadrant III, and autonomous in quadrant IV. The horizontal axis describes the level of dependency scale, whereas the vertical axis indicates the degree of influencing capacity.

Fig. 2 shows that access variable position (supply) in quadrant I or upper left, variable stakes (relay) in quadrant II or upper right, variable output in quadrant III or lower right, and variable autonomous in quadrant IV or lower left. The classification hinges on the extent of dependence, categorized as either high or low, and its effect on other variables. The critical variables are those that act as relays, fulfilling the function of conveying input variables to the output. Analysis results direct diagram influence/dependence in Fig. 3 explains

Table 4: Water utilization infrastructure

Description	Category	Frequency	%
Availability of infiltration/bio pores	Not available	128	56.9
	Available	97	43.1
	Total	225	100
Availability of rainwater storage	Not available	129	57.3
	Available	96	42.7
	Total	225	100
Availability of garden plants at home	Not available	27	12
	Available	198	88
	Total	225	100

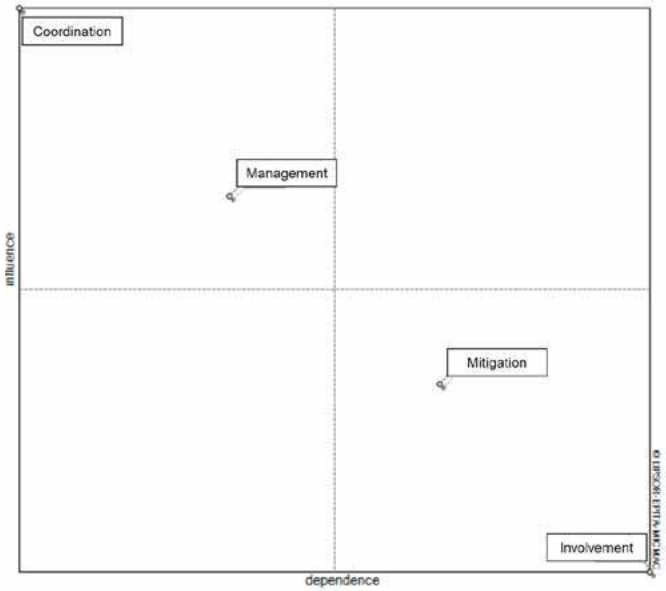


Fig. 2: Direct diagram influence/dependence

there is no variable in the variable position stakes (relay) or top right and variables autonomous in the bottom left position. In the context of access positions (supply), coordination and management variables are positioned in the upper left section, while mitigation variables and their corresponding involvement are found in the lower right section, which represents output. The micmac output that is classified as direct status indicates the prevailing conditions, while the indirect status is concerned with forecasting or potential future scenarios. The findings derived from the analysis, represented in the indirect diagram, clarify the repositioning of the managed and involved variables, which are largely concentrated in quadrant I. Overall, the differences between the direct and indirect diagrams are not markedly pronounced.

Policy making

Policy development that is guided by the findings of this micmac can be assessed by analyzing the matrix of potential direct influences (MPDI) and matrix of potential indirect influences (MPII). The two are distinguished by words direct (present) and indirect (future/forecast). Reading this output is the same as matrix of direct influences (MDI) or matrix of indirect influences (MII), the only difference is in MPDI and MPII, micmac has sorted the most important variables from highest to lowest values. The outcomes are sourced from MDI and MII, demonstrating a tendency to evolve due to designated iterations that take place in both the present and future contexts. Analysis results potential direct diagram influence/dependence in Fig. 4 explains that there are no variables in the variable position stakes (relay) or top right and variables autonomous in the bottom left position. Variables coordinate, management, and involvement in access positions (supply) or top left, and mitigation variables in position output or lower right. As depicted in Fig. 5, the relationship between the two variables exhibits a bidirectional influence in the current context. This illustration clarifies that the primary steps necessary to impact other variables are represented by the bold red lines. In the picture you can see the direction of influence starting from coordination, management and handling ending in involvement. Following this, the results pertaining to the potential indirect influence and dependence represented in the diagram will be discussed. The analysis reveals that, in general, there is little to no pronounced difference between the potential direct and indirect influences as shown in the diagram.

Fig. 6 shows that in the future conditions of the relationship influence between two variables tends to be one-way. In the sense that the potential of one

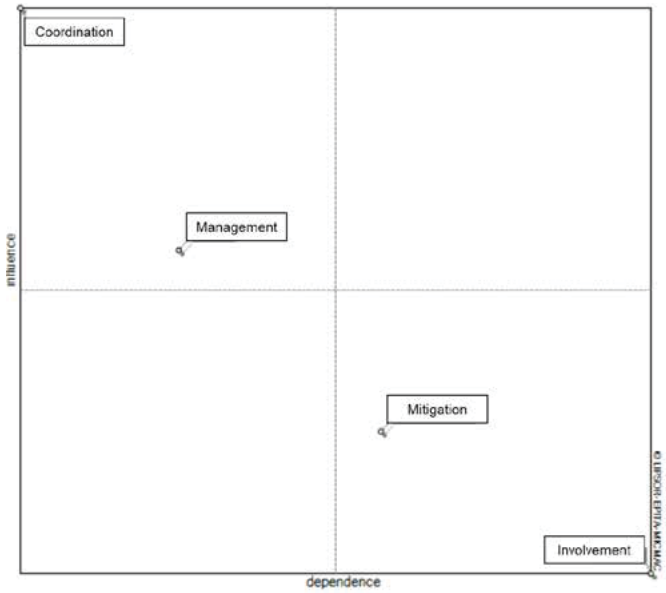


Fig. 3: Indirect diagram influence/dependence

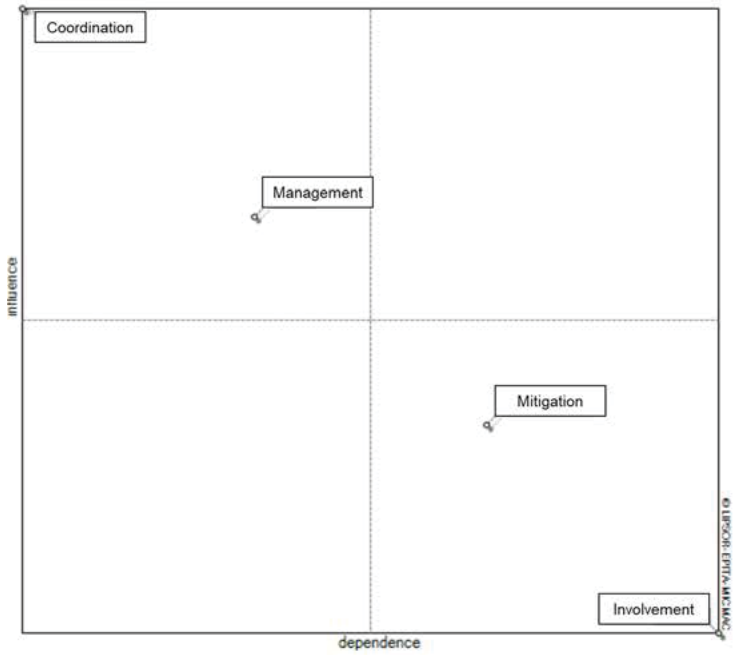


Fig. 4: Potential direct diagram influence/dependence

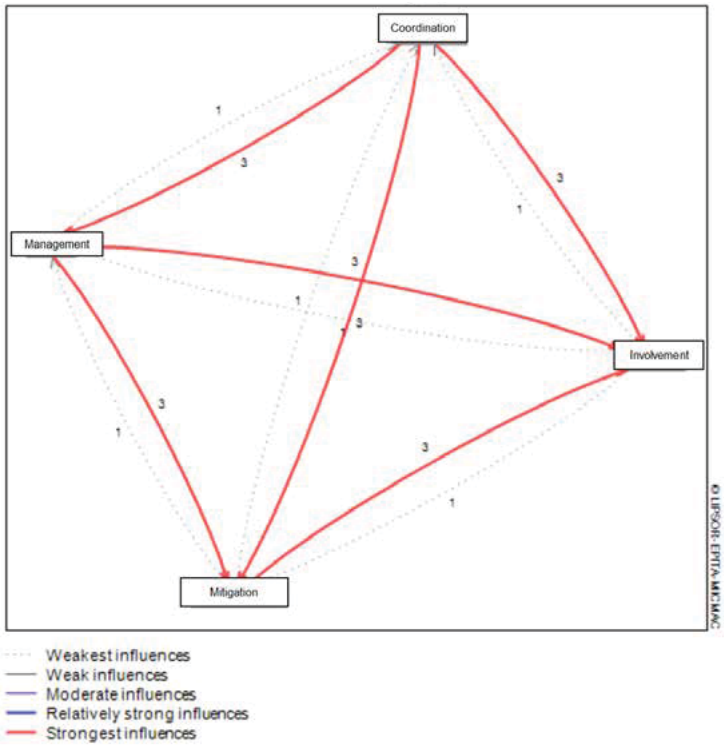


Fig. 5: Potential direct influence graph

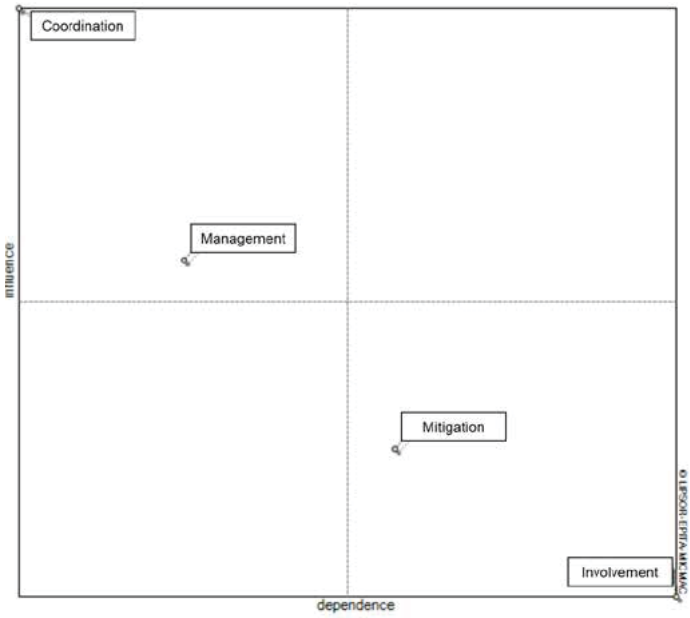


Fig. 6: Potential indirect diagram influence/dependence

variable has a single role (influence or dependence). An examination of the results reveals alterations in priority levels, as evidenced by the variables ranked according to their influence and those classified by their dependence.

The results of the analysis explain the potential shift in variable ranking in current conditions compared to future conditions (Fig. 7).

Tables 5 and 6 predicts that the variable priority level does not change in influencing other variables in the future. The order of being a variable that will influence other variables (influence), they are coordination, management, mitigation, and involvement. Variables can be classified according to their dependence on or the influence exerted by other variables. The most significant potential is found in those variables that are sequentially influenced by others, particularly in the domains of involvement, mitigation, management, and coordination. This analysis will assist policymakers in forecasting alterations in variables that both affect and are affected by other factors, thereby ensuring that the policies implemented are accurately aligned with their intended objectives.

In the context of transboundary governance and river management literature, coordination is often mentioned in conjunction with cooperation and collaboration, representing a mode of collective action or joint endeavor. It has been suggested that collaboration may be more effective in addressing the complexities of river basin issues and overcoming limitations in state capacity (Watson, 2004). Coordination is crucial in transboundary flood management because floods are rarely the result of a single cause (Clegg *et al.,* 2023). Several factors are instrumental in elevating the likelihood of flooding, which encompasses substantial rainfall, land subsidence, and human-induced activities like accelerated urbanization. Urbanization has increased the amount of impermeable surfaces, which reduces water infiltration and increases runoff (Remondi *et al*., 2016). Additionally, significant deforestation in the upper parts of the catchment area has exacerbated the problem (Asdak *et al*., 2018). The complexity of these interrelated issues indicates that no individual government agency or department is capable of independently addressing the challenges posed by flooding. Consequently, it is essential for both governmental and non-governmental organizations to engage in collaboration and coordination beyond conventional frameworks in order to amalgamate their resources and expertise.

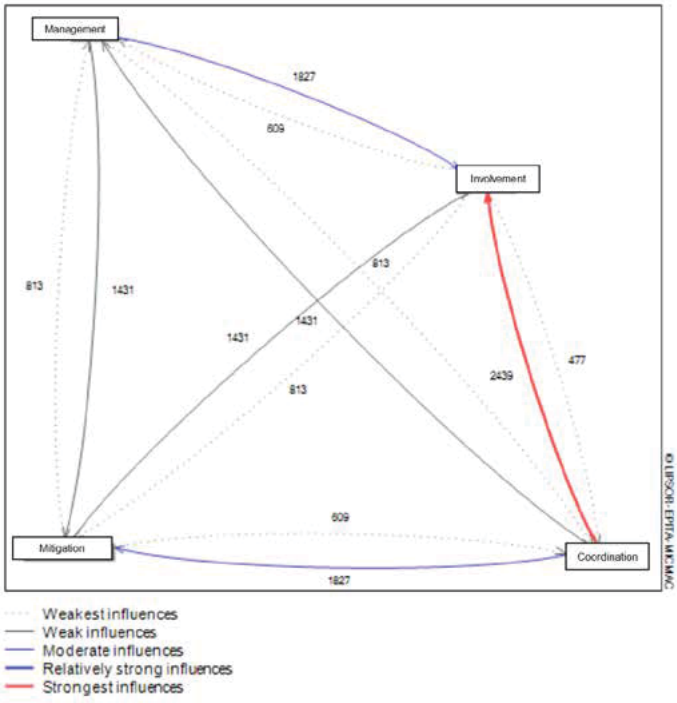


Fig. 7: Potential indirect influence graph

Table 5: Final weight of flood management strategy

Rank	Label	Direct influence	Indirect influence	Label	Direct dependence	Indirect dependence
1	Coordination	3750	3597	Involvement	3750	3597
2	Management	2916	2734	Overcome	2916	2734
3	Mitigation	2083	2087	Management	2083	2087
4	Involvement	1250	1581	Coordination	1250	1581

Table 6: Potential final weight of flood management strategy

Rank	Label	Potential Direct Influence	Potential Indirect Influence	Label	Potential direct dependence	Potential indirect dependence
1	Coordination	3750	3597	Involvement	3750	3597
2	Management	2916	2734	Overcome	2916	2734
3	Mitigation	2083	2087	Management	2083	2087
4	Involvement	1250	1581	Coordination	1250	1581

So, structural development and synergized with non-structural development that provides space for community behavior can minimizing flood disasters. Flood control measures are implemented in a holistic and coordinated fashion, encompassing stakeholder collaboration, effective flood disaster management, and community involvement. Various strategies can be employed to mitigate the impact of floods, including the following:

1. Coordination of technical stakeholders related to flood control:

The collaboration of technical stakeholders in flood control is a critical factor, presently

contributing 37.50% to the strategic framework, with an anticipated future contribution of 35.97%. Meanwhile, in its position as a strategy influenced by other strategies, it is currently 12.50%, and in the future 15.81%. So, this stakeholder coordination strategy has more of an influence on other strategies. The responsibility for flood control is shared among various stakeholders, including government agencies, the House of Representatives, private sector participants, and community groups. The government is fully responsible for resolv-ing disaster problems, especially flood disasters, in accordance with Law Number 24 of 2007. Effective stakeholder coordination may be accomplished through the allocation of tasks, functions, and roles to each participant, adhering to established regulatory frameworks. Granting authority for the provi-sion of road infrastructure and drainage channels to the Public Works and Spatial Plan-ning Department, and the Public Housing and Settlement Areas Department (Provincial and City), authority for the management of the Sail Watershed (Sumatra River Region III Office, Riau Province Public Works and Spatial Planning Department, and Pekanbaru City Public Works and Spatial Planning Department), authority regarding the granting of permits and supervision (Pekanbaru City Public Works and Spatial Planning Department and Pekanbaru City Investment and Integrated Services Department) and authority in handling flood disasters (National Agency for Disaster Countermeasure). It is within the government's purview to formulate regulations pertaining to spatial planning that also take into account the planning of waste disposal networks and potable water systems. Spatial planning can create networks planning to increase the reach of garbage trucks to the Sail Watershed area, increasing drinking water networks, waste selection education, etc.

2. Floodplain management:

From an ecohydrological perspective, river floodplains are vital and expansive ecosystems that absorb floodwaters, helping to reduce the risk of flooding. These floodplains serve a vital function in strengthening the resilience of river basins against the impacts of climate change, facilitating better flood safety, enhancing water quality, and offering a wider array ofecosystem services to society. Improving the natural capacity for water retention in floodplain regions and throughout the entire basin in the context of ongoing climate change can be accomplished through three distinct strategies: modeling the hydrological budget of the catchment for sustainable ecohydrological floodplain management, optimizing the use of existing hydrotechnical infrastructure, and implementing ecohydrological biotechnologies (Kiedrzyńska *et al*., 2015). The weight in the position as a strategy that will influence other strategies is 29.16%, and in the future, it has a weight of 27.34%. Meanwhile, the strategy's position, which is shaped by the influence of other strategies, stands at approximately 20.83%, with a projected increase to 20.87% in the future. This indicates that the floodplain management strategy possesses two defining characteristics that exert a slightly greater influence compared to other strategies. The strategy for structuring the area around the banks of the Sail River is more adaptive and sustainable, so as to reduce flooding problems around the river. Green open space planning is an ecosystem service for flood management (Schuch *et al*., 2017). The development of infrastructure and facilities aimed at supporting settlements includes the construction and upgrading of drainage channels, the establishment of temporary disposal sites, and the provision of piped potable water services. Supervise and monitor the granting of building approvals to buildings, especially housing and settlements in flood-prone areas.

3. Flood mitigation:

Flood management includes before a disaster occurs, during a disaster and after a disaster. The current weight of this position as a strategic element that will impact other strategies is approximately 20.83%, with a projected future weight of 20.87%. Meanwhile, the position as a strategy that is influenced by other strategies is currently around 29.16%, and in the future 27.34%. So, this flood management strategy in question possesses two defining characteristics that are influenced to a somewhat greater extent than those of alternative strategies. Flood mitigation involves measures implemented before, during, and after a flood occurrence. Prior to a flood, this is done by monitoring and evaluating data, reporting and identifying flood areas, providing maps of flood-prone areas,

implementing an early warning system, planning needs and providing funds, emergency response planning and implementing a flood information system. During a flood event, a series of actions are undertaken, which encompass flood management, the evacuation of residents and assets, the rescue of individuals, timely reporting, and the delivery of assistance for social needs. Subsequent to the flood, efforts are directed towards researching and evaluating the flood's repercussions, updating relevant data, and documenting the outcomes, as well as repairing any damage inflicted on flood control structures. Flood hazard areas are very high in areas with low-lying morphology, flat slopes, closed streams, expanding impermeable areas and intense urbanization (Bathrellos *et al*., 2016). Possible initiatives include the appropriate disposal of litter, the implementation of recycling programs, and the conservation of water. Such actions are expected to positively influence environmental conditions by lowering pollution levels, which in turn may lead to a decrease in the risk of flooding.

4. Community involvement:

The weight in the position as a strategy that will influence other strategies is currently around 12.50%, and in the future, it will have a weight of 15.81%. Meanwhile, the position as a strategy influenced by other strategies is currently around 37.50%, and in the future 35.97%. So, this community involvement strategy is more influenced by other strategies. The concept of community participation involves actions that are initiated before a disaster strikes, those that occur during the disaster, and efforts that follow the event. Community involvement was carried out in stages, starting with the stipulation of the Pekanbaru Mayor's Regulation regarding community participation in development (covering the community's role directly and indirectly in maintaining infrastructure), socialization/counseling in managing the environment, especially water use, healthy lifestyles, not throwing away rubbish. carelessly, managing used goods, implementing Clean and Healthy Living Behavior after the flood can minimize negative impacts on health (Trisasmita, 2022). Community engagement plays a vital role in clarifying the mapping and detailing the management conditions of drainage channels within the framework of flood control strategies (Ibrahim *et al*., 2021). Modifications in community practices, particularly regarding waste and water management, will enhance the likelihood of success in spatial planning initiatives aimed at flood mitigation. The government should provide education to the community about mitigation steps, so that they can be equipped with the information and skills needed to start and also take part in the implementation of spatial planning (Mohammed-Sittah and Siddique, 2023).

The concluding findings of the relationship map related to the four strategies, initiated by coordination, reveal that the most significant directional influence is from coordination to mitigation, management, and involvement. This indicates that the effectiveness of the other three strategies is contingent upon the optimal implementation of the coordination strategy by the regional government. It is evident that all strategic arrows converge towards the engagement strategy. This means that the quality of community involvement is largely determined by coordination, mitigation and management strategies. The interplay between mitigation and management strategies is characterized by their reciprocal influence on one another and on other strategic approaches, a phenomenon commonly termed mediation. As a result, the hierarchy of strategies, informed by analytical findings, is established in the following sequence: coordination, management, mitigation, and community involvement.

CONCLUSION

Spatial planning and the environment are closely related to each other. Currently, spatial planning/ development is only interpreted as physical development without considering the uniqueness of environmental behavior in a region. The development of a region necessitates the consideration of numerous factors. Beyond the physical aspects, it is imperative to also account for humanistic elements to attain a state of environmental harmony. Flood causes economic losses for affected communities, because of the repairs and replacement of damaged property and disruption of income. current flood disaster mitigation efforts often overlook socio-economic factors. This neglect signifies a critical flaw in flood mitigation strategies, as the individuals most at risk of flooding are often the ones whose

requirements are overlooked during the planning phase. In order to rectify these shortcomings, it is imperative that the management of floods and disaster response efforts prioritize socio-economic considerations as a fundamental principle. Therefore, appropriate spatial planning involving the important role of the community is the reason for conducting a study of the Influence of Spatial Planning and Community Behavior on Flood Control in the Sail Watershed, Pekanbaru City. This study innovation is a combination of the spatial concept of urban flooding phenomena and community behavior which has never been done before. This study demonstrates that coordination is the predominant variable, with a direct influence weight of 3750 and an indirect influence weight of 3597. Following coordination, the variables of management, mitigation, and involvement are identified as having lesser degrees of influence.. Coordination is crucial in transboundary flood management because floods are rarely the result of a single cause. Multiple factors contribute to increased flood risk, including heavy rainfall, land subsidence, and human activities such as rapid urbanization. To effectively reduce the impact of flood disasters, it is essential to pursue structural development while simultaneously incorporating non-structural strategies that encourage community participation. This dual approach can enhance the overall effectiveness of flood management efforts. Flood control efforts are implemented in an integrated and comprehensive manner starting from stakeholder coordination, flood plain management, flood management and involving the community. Modifications in community behavior are likely to enhance the effectiveness of spatial planning initiatives aimed at flood mitigation. Consequently, this will also contribute to a reduction in the flood risk within the region.

AUTHOR CONTRIBUTIONS

R. Dani performed the conceptualization, methodology, software analysis, validation, formal analysis, data curation, writing original draft, review and editing, visualization, and project administration. Sujianto performed the conceptualization, methodology, validation, review and editing, and supervision. Nofrizal performed the conceptualization, methodology, validation, review and editing, and supervision. B. Amin performed the conceptualization, methodology, validation, review and editing, and supervision.

ACKNOWLEDGEMENT

The authors express their sincere gratitude to Riau University for their essential resources and unwavering support, which were crucial for the successful completion of this study. This study received no external funding.

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

©2024 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
Fig.	Figure

GIS	Geographic information system
GOS	Green open space
ha	hectares
MDI	Matrix of direct influences
MII	Matrix of indirect influences
MPDI	Matrix of potential direct influences
MPII	Matrix of potential indirect influences
PPA	Participatory prospective analysis
USD	United State dollar

REFERENCES

Ahiablame, L.; Shakya, R., (2016). Modeling flood reduction effects of low impact development at a watershed scale. J. Environ. Manage. 171: 81-91 **(11 pages)**.

Aisha, T. S.; Wok, S.; Manaf, A. M. A.; Ismail, R., (2015). Exploring the use of social media during the 2014 flood in Malaysia. Procedia – Soc. Behav. Sci., 211: 931-937 **(7 pages)**.

Allegri, E.; Zanetti, M.; Torresan, S.; Critto, A., (2024). Pluvial flood risk assessment for 2021–2050 under climate change scenarios in the Metropolitan City of Venice. Sci. Total Environ., 914: 1-12 **(12 pages).**

Arvin, M.; Bazrafkan, S.; Beiki, P.; Sharifi, A., (2023). A county-level analysis of association between social vulnerability and COVID-19 cases in Khuzestan Province, Iran. Int. J. Disaster Risk Reduc. 84: 1-16 **(16 pages)**.

Asdak, C.; Supian, S.; Subiyanto. (2018). Watershed management strategies for flood mitigation: A case study of Jakarta's flooding. Weather Clim. Extremes. 21(9): 117-122 **(6 pages)**.

Bathrellos, G.D.; Karymbalis, E.; Skilodimou, H.D.; Gaki-Papanastassiou, K.; Baltas, E.A., (2016). Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece. Environ. Earth Sci., 75(4): 1-14 **(14 pages).**

Bathurst, J.C.; Birkinshaw, S.J.; Cisneros Espinosa, F.; Iroum'e, A., (2016). Forest impact on flood peak discharge and sediment yield in streamflow. River Syst. Anal. Manage.: 15-29 **(15 pages)**.

Boulange, J.; Hanasaki, N.; Yamazaki, D.; Pokhrel, Y., (2021). Role of dams in reducing global flood exposure under climate change. Nat. Commun., 12(1): 1-7 **(7 pages)**.

Brown, P.H.; Tullos, D.; Tilt, B.; Magee, D.; Wolf, A.T., (2009). Modeling the costs and benefits of dam construction from a multidisciplinary perspective. J. Environ. Manage., 90: S303–S311 **(9 pages)**.

Buisan, Z.A.; Milano, A.E.; Suson, P.D.; Mostrales, D.S.; Taclendo, C.S.; Blasco, J.G., (2019). The impact of sound land use management to reduce runoff. Global J. Environ. Sci. Manage., 5 (4): 399-414 **(16 pages)**.

Butler, C.; Walker-Springett, K.; Adger, W.N.; Evans, L.; O'Nell, S.J.; Adger, N., (2016). Social and Political Dynamics of Flood Risk, Recovery, and Response. London: University of Exeter.

Cao, G.; Liu, P.; Cao, R., (2024). Resident motivations, policy types and multisphere waste sorting intentions in China from a dual-interest integration perspective: An expanded goal-framing theory. Environ. Impact Assess. Rev., 108: 1-24 **(24 pages).**

Chakraborty, L.; Thistlethwaite, J.; Scott, D.; Henstra, D.; Minano, A.; Rus, H., (2023). Assessing social vulnerability and identifying spatial hotspots of flood risk to inform socially just flood management policy. Risk Anal., 43 (5): 1058-1078.

Chen, X.; Zhang, H.; Chen, W.; Huang, G., (2021). Urbanization and climate change impacts on future flood risk in the Pearl River Delta under shared socioeconomic pathways. Sci. Total Environ. 762: 1-14 **(14 pages)**.

Chen, Y.; Zhou, H.; Zhang, H.; Du, G.; Zhao, J., (2015). Urban flood risk warning under rapid urbanization. Environ. Res. 139: 3-10 **(8 pages)**.

Cheon, J.P.; Son, J.; Ahn, Y., (2024). Economic and environmental factor-integrated optimal model for plastic-waste sorting. J. Ind. Eng. Chem.: 1-13 **(13 pages).**

Clegg, G.; Haigh, R.; Amaratunga, D.; Rahayu, H.P., (2023). Coordination challenges facing effective flood governance in the Ciliwung River Basin. Cham: Springer **(15 pages)**.

Coombes, P.J., (2023). Urban flood risks, water law and insurance: The intersection of emerging science, practice and authority. Precedent. 170: 4-9 **(6 pages)**.

Damai, A.A.; Boer, M.; Marimin; Damar, A.; Rustiadi, E., (2011). Participatory Prospective Analysis in Coastal Zone Management of Lampung Bay. Forum Pascasarjana. 34 (4): 281-296 **(16 pages)**.

Fischer, S.; Schumann, A.H., (2024). Temporal changes in the frequency of flood types and their impact on flood statistics. J. Hydrol., 22: 1-14 **(14 pages)**.

Forrest, S.A.; Trell, E.M.; Woltjer, J., (2020). Socio-spatial inequalities in flood resilience: Rainfall flooding in the city of Arnhem. Cities. 105: 1-15 **(15 pages)**.

Genovese, E.; Thaler, T., (2020). The benefits of flood mitigation strategies: effectiveness of integrated protection measures. AIMS Geosci., 6 (4): 459-472 **(14 pages)**.

Hallegatte, S.; Green, C.; Nicholls, R.J.; Corfee-Morlot, J., (2013). Future flood losses in major coastal cities. Nat. Clim. Change. 3(9): 802-806 **(5 pages)**.

Hazzam, J., (2022). The moderating role of age on social media marketing activities and customer brand engagement on Instagram social network. Young Consumers, 23 (2): 197-212 **(16 pages)**.

Hibbard, M.; Lurie, S., (2000). Saving land but losing ground: Challenges to community planning in the era of participation. J. Plan. Educ. Res., 20(2): 187-195 **(9 pages)**.

Ibrahim, A.S.; Memon, F.A.; Butler, D., (2021). Seasonal variation of rainy and dry season per capita water consumption in freetown city sierra Leone. Water. 13(4):

1-28 **(28 pages)**.
Jin, H.; Liang, Y.; Lu, H.; Zhang, S.; Gao, Y.; Zhao, Y.; Zhu, Z., (2024). An intelligent framework for spatiotemporal simulation of flooding considering urban underlying surface characteristics. Int. J. Appl. Earth Obs. Geoinf., 130: 1-10 **(10 pages)**.
Kiedrzyńska, E.; Kiedrzyński, M.; Zalewski, M., (2015). Sustainable floodplain management for flood prevention and water quality improvement. Nat. Hazard., 76(2): 955–977 **(23 pages)**.
Kittipongvises, S.; Phetrak, A.; Rattanapun, P.; Brundiers, K.; Buizer, J.L.; Melnick, R., (2020). AHP-GIS analysis for flood hazard assessment of the communities nearby the world heritage site on Ayutthaya Island, Thailand. Int. J. Disaster Risk Reduct., 48: 1-17 **(17 pages)**.
Kurniawan, R.; Nasution, B.I.; Agustina, N.; Yuniarto, B., (2022). Revisiting social vulnerability analysis in Indonesia data. Data Brief. 40: 1-7 **(7 pages)**.
Li, X.N., Li, Y.L., Zheng, S.W., Chen, G., Zhao, P.X., Wang, C.H., (2024). High efficiency integrated urban flood inundation simulation based on the urban hydrologic unit. J. Hydrol., 630: 1-12 **(12 pages)**.
Liang, C.Y.; You, G.J.Y.; Lee, H.Y., (2019). Investigating the effectiveness and optimal spatial arrangement of low-impact development facilities. J. Hydrol., 577: 1-17 **(17 pages)**.
Lin, L.Y.; Lin, C.T.; Chen, Y.M.; Cheng, C.T.; Li, H.C.; Chen, W.B., (2022). The Taiwan climate change projection information and adaptation knowledge platform: A decade of climate research. Water. 14(3): 1-12 **(12 pages)**.
Liu, W.; Chen, W.; Peng, C., (2014). Assessing the effectiveness of green infrastructures on urban flooding reduction: a community scale study. Ecol. Model., 291: 6-14 **(9 pages)**.
Luo, X.; Lu, J.; Apuke, O. D., (2024). Understanding the impact of computer-based technology storytelling for help seeking and help receiving among victims of flood disaster. Comput. Hum. Behav., 153: 1-7 **(7 pages)**.
Malalgoda, C.; Amaratunga, D.; Haigh, R., (2016). Overcoming challenges faced by local governments in creating a resilient built environment in cities. Disaster Prev. Manage., 25(5): 628–648 **(21 pages)**.
Mehryar, S.; Surminski, S., (2022). Science of the total environment investigating flood resilience perceptions and supporting collective decision-making through fuzzy cognitive mapping. Sci. Total Environ., 837: 1-13 **(13 pages)**.
Mei, C.; Shi, H.; Liu, J.; Song, T.; Wang, J.; Gao, X.; Wang, H.; Li, M., (2024). Analysing urban form influence on pluvial flooding via numerical experiments using random slices of actual city data. J. Hydrol., 633: 1-13 **(13 pages)**.
Mohammed-Siitah, R.; Siddique, A., (2023). Spatial planning and community adaptive capacity to climate change: the case of La Dade-Kotopon municipality in Ghana. Journal of Property Planning and Environmental Law. 15 (2): 63-82 **(20 pages)**.
Moller-Jensen, Y.; Agergaard, J.; Andreasen, M.H.; R.Y.; Yiran, G.A.; Oteng-Ababio, M., (2023). Probing political paradox: urban expansion, floods risk vulnerability and social justice in urban Africa. J. Urban Aff., 45 (3): 505-521 **(17 pages)**.
Munoz, R.; Vaghefi, S.A.; Sharma, A.; Muccione, V., (2024). A framework for policy assessment using exploratory modelling and analysis: An application in flood control. Clim. Risk Manage., 45: 1-15 **(15 pages)**.
NADC, (2022). Indonesian Disaster Risk Index. Jakarta: National Agency for Disaster Countermeasure **(354 pages)**.
Narendra, B.H.; Setiawan, O.; Hasan, R.A.; Siregar, C.A.; Pratiwi, Sari, N.; Sukmana, A.; Dhamawan, I.W.S.; Nandini, R., (2024). Flood susceptibility mapping based on watershed geomorphometric characteristics and land use/land cover on a small island. Global J. Environ. Sci. Manage. 10(4): 301-320 **(20 pages)**.
Nasution, B.I.; Saputra, F.M.; Kurniawan, R.; Ridwan, A.N.; Fudholi, A.; Sumargo, B., (2022). Urban vulnerability to floods investigation in jakarta, Indonesia: A hybrid optimized fuzzy spatial clustering and news media analysis approach. Int. J. Disaster Risk Reduct. 83: 1-17 **(17 pages)**.
Njoku, P.O.; Durowoju, O.S.; Uhunamure, S.E.; Makungo, R., (2022). Investigating the Attitude of Domestic Water Use in Urban and Rural Households in South Africa. Water. 14(2): 1-15 **(15 pages).**
Owolabi, T.A.; Mohandes, S.R.; Zayed, T., (2022). Investigating the impact of sewer overflow on the environment: A comprehensive literature review paper. J. Environ. Manage., 301: 1-15 **(15 pages)**.
PCPWSPD, (2020). Pekanbaru City Flood Control Masterplan. Pekanbaru: Pekanbaru City Public Works and Spatial Planning Department.
Pour, S.H.; Abd Wahab, A.K.; Shahid, S.; Asaduzzaman, M.; Dewan, A., (2020). Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: current trends, issues and challenges. Sustain. Cities Soc. 62: 1-14 **(14 pages)**.
Putra, A.A.S.; Sandhyavitri, M.; Fauzi, (2016). Identification of Significant Parameters in Determining Priorities for Handling Floods in Pekanbaru City. J. Online Mahasiswa Fakultas Teknik Universitas Riau. 3(2): 1-9 **(9 pages)**.
Qi, W.; Liu, Y.; Ma, C.; Xu, H.; Lian, J.; Xu, K.; Yao, Y., (2024). A combined qualitative-quantitative method for adaptive configuration of urban flood mitigation measures. Urban Clim., 56: 1-18 **(18 pages)**.
Qi, W.C.; Ma, C.; Xu, H.S.; Zhao, K., (2022). Urban flood response analysis for designed rainstorms with different characteristics based on a tracer-aided modelling simulation. J. Clean. Prod., 355: 1-11 **(11 pages)**.
Remondi, F.; Burlando, P.; Vollmer, D., (2016). Exploring the hydrological impact of increasing urbanisation on a tropical

river catchment of the metropolitan Jakarta, Indonesia. Sustainable Cities Soc., 20: 210-221 **(12 pages)**.

Rouhanizadeh, B., (2020). Analysis of Barriers Causing Delay in Post-hurricane Recovery: Experts vs. Public's Perspectives. Doctoral dissertation. The University of Texas at Arlington **(138 pages)**.

Rouhanizadeh, B; Safapour, E., (2024). A MAP-based approach to identify the social vulnerability to flood hazard in states adjacent to Mexican Gulf. Int. J. Disaster Risk Reduct., 111: 1-17 **(17 pages)**.

Russell, S. V.; Knoeri, C., (2020). Exploring the psychosocial and behavioural determinants of household water conservation and intention. Int. J. Water Resour. Dev., 36(6): 940-955 **(16 pages)**.

Sarwono, J., (2011). Mixed Methods How to Combine Quantitative and Qualitative Research Correctly. Jakarta: Elex Media Komputindo **(204 pages)**.

Schuch, G.; Serrao-Neumann, S.; Morgan, E.; Low Choy, D., (2017). Water in the city: Green open spaces, land use planning and flood management – An Australian case study. Land Use Policy. 63: 539-550 **(12 pages)**.

Sharp, E.N.; Carter, H., (2020). Examination of how social media can inform the management of volunteers during a flood disaster. J. Flood Risk Manage., 13(4): 1-10 **(10 pages)**.

Simonovic, S.P.; Carson, R.W., (2003). Flooding in the Red River Basin - Lessons from Post Flood Activities. Nat. Hazard. 28: 345-365 **(21 pages)**.

SPM, (2022). Pekanbaru Municipality in Figures. Pekanbaru: Statistics of Pekanbaru Municipality **(388 pages)**.

Srivanit, M.; Pattanasri, S.; Phichetkunbodee, N.; Manokeaw, S.; Sitthikankun, S.; Rinchumphu, D., (2024). Analysis of sensitive urban form indicators of flood susceptible prediction based on machine learning models. Global J. Environ. Sci. Manage., 10 (4): 1501-1518 **(18 pages)**.

Sugiyono, (2017). Qualitative quantitative research methodology and R&D. Bandung: Alpabeta **(334 pages)**.

Suryani, S.; Ningsih, K.W., (2019). Factors influencing the behavior of throwing garbage in the sago river, pekanbaru. Health care: J. Kesehatan. 7(2): 52-56 **(5 pages)**.

Susilo, (2019). Analysis and Mapping of Flood-Prone Areas Based on Geographic Information Systems (GIS) in Pekanbaru City, Riau Province. Pekanbaru: Universitas Islam Riau **(62 pages)**.

Talabi, F.O.; Aiyesimoju, A.B.; Lamidi, I.K.; Bello, S.A.; Okunade, J.K.; Ugwuoke, C.J.; Gever, V.C., (2022). The use of social media storytelling for help-seeking and help-receiving among Nigerian refugees of the Ukraine–Russia war. Telematics and Informatics. 71: 1-10 **(10 pages).**

Texier-Teixeira, P.; Edelblutte, E., (2017). Jakarta: Mumbai—two megacities facing floods engaged in a marginalization process of slum areas. Migration Clim Chang Sustainanable Dev. Shap Debates Policies. 81-99 **(19 pages)**.

Trisasmita, L., (2022). Post-flood education and socialization of clean and healthy living behavior. Sarwahita. 19 (3): 434-448 **(15 pages)**.

Turkington, T.; Breinl, K.; Ettema, J.; Alkema, D.; Jetten, V., (2016). A new flood type classification method for use in climate change impact studies. Weather Clim. Extremes. 14: 1-16 **(16 pages)**.

Wan, J.; Qin, Y.; Shen, Y.; Yang, T.; Yan, X.; Zhang, S.; Yang, G.; Xue, F.; Wang, Q.J., (2024). Automatic detection of urban flood level with YOLOv8 using flooded vehicle dataset. J. Hydrol., 639: 1-9 **(9 pages)**.

Wang, Y.; Shen, Y.; Salahshour, B.; Cetin, M.; Iftekharuddin, K.; Tahvildari, N.; Huang, G.; Harris, D.K.; Ampofo, K.; Goodall, J.L., (2024). Urban flood extent segmentation and evaluation from real-world surveillance camera images using deep convolutional neural network. Environ. Modell. Software. 173: 1-11 **(11 pages)**.

Watson, N., (2004). Integrated river basin management: A case for collaboration. Int. J. River Basin Manage., 2(4): 243-257 **(15 pages)**.

Winsemius, H.C.; Jongman, B.; Veldkamp, T.I.; Hallegatte, S.; Bangalore, M.; Ward, P.J., (2018). Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. Environ. Dev. Econ., 23 (3): 328-348 **(21 pages)**.

Yan, L.; Rong, H.; Yang, W.; Lin, J.; Zheng, C., (2024). A novel integrated urban flood risk assessment approach based on one-two dimensional coupled hydrodynamic model and improved projection. J. Environ. Manage., 366: 1-16 **(16 pages)**.

Yang, L.; Ji, X.; Li, M.; Yang, P.; Jiang, W.; Chen, L.; Yang, C.; Sun, C.; Li, Y. (2024). A comprehensive framework for assessing the spatial drivers of flood disasters using an optimal Parameter-based geographical Detector–machine learning coupled model. Geosci. Front., 15(6): 1-16 **(16 pages)**.

Zhang, Z.; Huang, G., (2024). Flood resilience assessment of metro station entrances based on the PSR model framework: A case study of the Donghaochong Basin, Guangzhou. J. Environ. Manage., 366: 1-10 **(10 pages)**.

Zhou, Y.; Peng, T.; Shi, R., (2019). Research progress on risk assessment of heavy rainfall and flood disasters in China. Torrential Rain Disasters. 38 (5): 494-501 **(8 pages)**.

Zhu, S.; Li, D.; Feng, H.; Zhang, N., (2023). The influencing factors and mechanisms for urban flood resilience in China: From the perspective of social-economic-natural complex ecosystem. Ecol. Indic., 147: 1-14 **(14 pages)**.

Zhu, S.; Li, D.; Huang, G.; Chhipi-Shrestha, G.; Nahiduzzaman, K.M.; Hewage, K.; Sadiq, R., (2021). Enhancing urban flood resilience: A holistic framework incorporating historic worst flood to Yangtze River Delta, China. Int. J. Disaster Risk Reduct., 61: 1-15 **(15 pages)**.

AUTHOR (S) BIOSKETCHES

Dani, R., M.Si., Environmental Science Program, Riau University, Bina Widya KM Campus. 12.5, Simpang Baru, Tampan District, Pekanbaru City, Riau Province, Indonesia.
- Email: *risqiana2010@gmail.com*
- ORCID: 0000-0003-0024-5238
- Web of Science ResearcherID: LBI-1776-2024
- Scopus Author ID: NA
- Homepage: https://garuda.kemdikbud.go.id/author/view/5879133

Sujianto, Ph.D., Faculty of Social and Political Science, Riau University, Bina Widya KM Campus. 12.5, Simpang Baru, Tampan District, Pekanbaru City, Riau Province, Indonesia.
- Email: *sujianto0926@gmail.com*
- ORCID: 0009-0008-5398-5196
- Web of Science ResearcherID: LBI-1751-2024
- Scopus Author ID: NA
- Homepage: https://sinta.kemdikbud.go.id/authors/profile/6012401

Nofrizal, Ph.D., Faculty of Fisheries and Marine, Riau University, Bina Widya KM Campus. 12.5, Simpang Baru, Tampan District, Pekanbaru City, Riau Province, Indonesia.
- Email: *nofrizal@lecturer.unri.ac.id*
- ORCID: 0000-0002-9623-1684
- Web of Science ResearcherID: GPK-4661-2022
- Scopus Author ID: 35722480900
- Homepage: https://sinta.kemdikbud.go.id/authors/profile/6033879

Amin, B., Ph,D., Faculty of Fisheries and Marine, Riau University, Bina Widya KM Campus. 12.5, Simpang Baru, Tampan District, Pekanbaru City, Riau Province, Indonesia.
- Email: *bintal.amin@lecturer.unri.ac.id*
- ORCID: 0000-0003-3951-7042
- Web of Science ResearcherID: AAA-1011-2022
- Scopus Author ID: 23491429700
- Homepage: https://sinta.kemdikbud.go.id/authors/profile/24583

HOW TO CITE THIS ARTICLE

Dani, R.; Sujianto; Nofrizal; Amin, B., (2024). Spatial planning strategies and community behavior towards flood control. Global J. Environ. Sci. Manage., 10(SI): 303-322.

DOI: 10.22034/gjesm.2024.10.SI.19

URL: https://www.gjesm.net/article_715377.html

Global J. Environ. Sci. Manage. 10(SI): 323-348, 2024

Global Journal of Environmental Science and Management
(GJESM)

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

Podcasts

REVIEW PAPER

Intervention strategy for sustainable waste management systems in developing countries using community of practice

Sunarti[1,*], M. Nuryana[1], W. Wiryanto[1], Buyamin[1], A. Aswin[1], C. Permatasari[1], J.H. Tjakraatmadja[2]

[1] *Research Center for Public Policy, National Research and Innovation Agency, Jl. Gatot Subroto, Kuningan Bar., Kec. Mampang Prapatan, Kota Jakarta Selatan, DKI Jakarta, 12710, Indonesia*

[2] *School of Business and Management, Bandung Institute of Technology, Jl. Ganesa, Lebak Siliwangi, Jawa Barat, Kota Bandung, 40132, Indonesia*

ARTICLE INFO

Article History:
Received 29 May 2024
Revised 01 July 2024
Accepted 06 September 2024

Keywords:
Collaborative System
Community of practice (CoP)
Developing countries
Public participation
Waste management

ABSTRACT

Collaborative systems from various sectors, including public community, are encouraged to tackle the complexity of waste problems. Nonetheless, the task of identifying the most effective intervention strategies that encourage sustainable participation in collaborative initiatives remains a formidable challenge. Evidence from various studies suggests that utilizing a community of practice platform for social learning fosters collaboration and supports collective learning, which is essential for driving transformative change in the field of waste management. This study aimed to diagnose the characteristics of expected intervention strategies to sustain community participation in waste management program from past studies conducted in developing countries. The study further explored the feasibility of establishing a community of practice in the area of waste management. Using a literature review method, this study selected and analysed thoroughly 52 papers related to waste management topics and 31 papers related to community of practice implementation in various domains, especially environmental management and waste management issues. The selected papers were thoroughly examined and categorized through the application of qualitative data analysis software. There were 2 categories to map the content of the studies related to waste management topics, while 2 categories and 7 sub-categories were used to map the content of the selected papers on Community of Practice topic. The investigation revealed that the integration of social learning via a Community of Practice platform is viable for waste management systems in developing countries. This method can enhance multi-loop learning processes, encompassing single-loop learning that drives technical improvements, double-loop learning that encourages reflective thinking to initiate changes in mindset or psychological frameworks, and triple-loop learning that supports comprehensive systemic change. Research has demonstrated that multi-loop learning drives significant transformation from the individual level to the system, thereby bolstering the new waste management paradigm. The community of practice also enables collaborative action from multi-stakeholders across sectors and across organization at various level, which is crucial for the effectiveness of collaborative waste management system. The primary contribution and innovative aspect of this study is the introduction of a model that thoroughly elucidates the interconnections among various stakeholders across different levels and sectors within the waste management system at both local and regional scales. It also suggested a multi loop learning model that describe the expected learning cycles in the waste management system which have not been found in any previous studies. This finding is crucial for policymakers and government agencies in many developing countries to find new insight to improve waste management system through collaboration that enable social learning among involved stakeholders. More extensive investigations are needed to examine the proposed community of practice model and to quantify its influence and effectiveness in promoting learning outcomes throughout every learning loop.

DOI: 10.22034/gjesm.2024.10.SI.20

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

NUMBER OF REFERENCES
106

NUMBER OF FIGURES
5

NUMBER OF TABLES
5

*Corresponding Author:
Email: *suna036@brin.go.id*
Phone: +62813 2511 5551
ORCID: 0000-0002-6332-5190

Note: Discussion period for this manuscript open until November 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Public participation in waste management system has been opted as the best solution for waste management program especially in developing countries (Sewak *et al.*, 2021). The engagement of diverse sectors and stakeholders, including civil society, is essential for effective waste management practices (Anuardo *et al.*, 2022; Einhäupl *et al.*, 2019; Vlachokostas, 2020). Yet, MSWM in many developing countries is mostly relied upon the local government to handle the waste along the stream (Banerjee and Sarkhel, 2020). Given the multifaceted aspects of environmental problems, effective resolution demands a collaborative approach among various stakeholders (Arantes, Zou and Che, 2020). Therefore, it requires paradigm shift or transformative change which is not only at how waste management should be performed, but also re-thinking about the role of human-nature relationship and how governance should be evolved from government-centric to collaborative governance where complex stakeholders contribute to the policy development as well as its implementation (Fulgenzi *et al.*, 2020; King *et al.*, 2023; Pahl-Wostl, 2009). Understanding the multifaceted aspects of the human dimension is vital for promoting a paradigm shift in waste management, rather than concentrating solely on technical solutions (Pahl-Wostl, 2009). Lack of public participation from the downstream to the upstream caused costly operational fundings and ineffective waste management process (Odhiambo *et al.*, 2021). It becomes a huge problem for developing countries which typically have limited budget for waste management (Abbasi, 2018). The collaboration is designed to include a broader range of participants, not solely restricted to non-public stakeholders like private entities and non-governmental organizations (NGOs) (Arantes *et al.*, 2020), but should include civil society as well, whether as individuals or as community groups because of their primary roles in dealing with waste from the source (Izdebska and Knieling, 2020). Collaboration in the realm of waste management serves a dual purpose: it not only aims to prevent the constraints associated with policy enforcement but also encourages stakeholder engagement in the decision-making process and fosters collective initiatives for waste management, addressing prevention, recovery, and disposal. Thus, the collaboration is requisite to raise community awareness, positive attitude and responsibility of the public society (Ghazali *et al.*, 2023), to share resources and time among collaborators (Arantes *et al.*, 2020; Didham *et al.*, 2017) and to add more value in waste streams (Einhäupl *et al.*, 2019). Even though public participation in waste management system is vital, either at civil society level or organizational level, some problems were still emerged according to previous studies. Certain initiatives aimed at promoting civil society engagement may yield only short-term results, ultimately leading to a lack of significant improvement in participatory outcomes (Atta *et al.*, 2023; Gyimah *et al.*, 2019; Nepal *et al.*, 2023; Sayara *et al.*, 2022; Singer *et al.*, 2019; Wang and Huo, 2023; Zamri *et al.*, 2020). Some previous studies only focused on collaboration at organizational level without involving civil society into the discussion whereas civil society's role is crucial especially at downstream (Johnson and Wilson, 2000; Odhiambo *et al.*, 2021). Some further suggested collaboration often results unfriendly situation due to incoordination among parties (Ain *et al.*, 2020; Sun, 2015; Tobin and Zaman, 2022). Different collaborative efforts highlighted the importance of government involvement, yet they yielded a limited degree of participation from public communities (Zhang and Zhu, 2022; Ain *et al.*, 2020). In this vein, social learning is suggested to be the answer, as social learning can facilitate discussion, intensive interaction, and enable collaboration among parties with different roles, to nurture stakeholder capacity, to build trust and bonding, to achieve shared norm on a certain domain, and to promote behavioural change and perform transformative change collectively (Bonatti *et al.*, 2022; King *et al.*, 2023; Pahl-Wostl, 2009; Sunarti *et al.*, 2023). Social learning performs multi loop learning that enables gradual level of individual and collective learning (Pahl-Wostl, 2009; Wenger, 2010), starting from improvement on established action to reflecting the action, adjusting and transforming the structure, governance and norms contextually as a result of social and institutional change (Fulgenzi *et al.*, 2020; King *et al.*, 2023; Noguera-Méndez *et al.*, 2016). Therefore, social learning contributes to both individual and collective learning processes, as well as institutional learning, which collectively underpin the collaborative systems recommended for more effective waste management initiatives. The successful execution of social learning requires a

structured platform or framework that enables collaborative activities, one notable example being a community of practice (CoP) (King *et al.*, 2023; Reed *et al.*, 2014). CoP is an informal platform that facilitate knowledge co-production process to occur among members in certain domain, including sharing insights, experiences, techniques, behavior imitation, and also joint activities among members from diverse level to reach shared goals (Ddiba *et al.*, 2020; Fulgenzi *et al.*, 2020). Thus, social learning is not only able to improve public participation from civil society level, either as individuals or social community, but also organizational and systemic level which is important for collaboration. Although there is significant potential for implementing strategies that promote collaboration in waste management systems, there is still a notable scarcity of studies addressing social learning and Communities of Practice (CoP) specifically within this field. Some previous studies discussed CoP for its implementation in other environmental management domain such as agro-ecosystem resilience strategies for Greater Blue Mountains World Heritage Area in Australia (Merson *et al.*, 2011), Biological conservation in Canada (Reed *et al.*, 2014), circular economy on water management system in Europe (Fulgenzi *et al.*, 2020), natural flood management in Yorkshire, UK (King *et al.*, 2023), involving various parties across level and organizations including civil society. Research pertaining to Communities of Practice (CoP) in the context of waste management has been discovered, albeit with a restricted scope. Notably, three studies examined the implementation of CoP at both individual and community group levels, focusing exclusively on behavioral change as the resultant output of this implementation (Ghazali *et al.*, 2021; Kim, 2017; Sunarti *et al.*, 2023). One study discussed activities in CoP across-community level (Bonatti *et al.*, 2022) but did not propose any CoP model to be a reference for CoP implementation. Various studies have examined the activities associated with CoP that operate across different organizational tiers (Ddiba *et al.*, 2020; Johnson and Wilson, 2000) or within multinational corporations (Odhiambo *et al.*, 2021). Nonetheless, these investigations have overlooked the role of civil society, including individuals and community groups, and have failed to propose a framework for CoP implementation. Only two studies proposing models for CoP implementation, one study developed and proposed a CoP model for climate change on farming system (Raymond and Robinson, 2013) but only involved professionals and community group without involving civil society. The other study was about CoP implementation in waste management context (Ghazali *et al.*, 2021), but did not describe more details about its network across sectors and level and there was no proposed model of learning process that showed the outcome for every learning loop. Consequently, in order to bridge this gap, the study has established the following objectives. The first objective is to analyze the feasibility of implementing CoP within waste management systems, with a specific emphasis on fostering public engagement at the level of civil society. Second, proposed a CoP model for waste management context implementation that involve more diverse parties across sectors and level. Third, developed a multi-loop learning model occur in CoP for waste management context.

Social learning and community of practice

Social learning functions as an informal network that encourages discussion, the sharing of knowledge, and the co-creation of ideas among individuals from various fields of expertise, thereby fostering collaboration aimed at achieving collective transformation (Gars and Ward, 2019; King *et al.*, 2023; Pahl-Wostl, 2009). The core point of social learning framework is learning and collective change, offering a strategy to address complex socio-ecological issues such as water resource resilience, environmental and waste problems by integrating various activities of knowledge and value sharing at distinct level by way of multiple learning cycles (Keen and Mahanty, 2006; Noguera-Méndez *et al.*, 2016; Pahl-Wostl, 2009). The concept of social learning encompasses a multitude of forms, enabling significant transformations that impact individuals as well as organizations on a collective scale (Fulgenzi *et al.*, 2020; King *et al.*, 2023; Kristjanson *et al.*, 2014; Pahl-Wostl, 2009). The learning activities among stakeholders from different levels and different roles enable change on their knowledge and understanding as well as intrinsic or affective factors as a result of the critical reflection of the value from the activities (Fulgenzi *et al.*, 2020; King *et al.*, 2023; Noguera-Méndez *et al.*, 2016). One platform to facilitate social learning is CoP (Noguera-Méndez *et al.*, 2016; Wenger, 2010; Wenger *et al.*, 2002). CoP refers to an informal collective comprising

various participants who regularly partake in a social learning process. Through active engagement and the sharing of issues, interests, and concerns regarding a particular topic, members aim to deepen their understanding and expertise in that domain (Beattie *et al.*, 2022; King *et al.*, 2023; Wenger *et al.*, 2002). There is a participatory process in knowledge transfer activity in CoP that stimulate social learning (Fulgenzi *et al.*, 2020). CoP has become a management tool which connect distinct actors, even if they are dispersed geographically to interact and engage and to knowledge co-creation process (Beattie *et al.*, 2022; Fulgenzi *et al.*, 2020). CoP has three dimensions named Domain, Community and Practice (Wenger *et al.*, 2002). The term domain signifies a collective topic or area of interest, while community pertains to the individuals engaged in knowledge-sharing endeavors. In contrast, practice refers to the collaborative approaches and techniques that these members adopt concerning their domain, leveraging the resources available to them (Fulgenzi *et al.*, 2020; Wenger, 2010).

Multi loop learning theory

Multi loop learning is a theory that explain the degree of social learning, applied in collaborative learning context (King *et al.*, 2023; Pahl-Wostl, 2009). There are three degree of learning loops, named single loop, double loop and triple loop learning. Single loop learning is a foundational learning process that emphasizes the improvement of actions and the rectification of mistakes within established routines. This method seeks to optimize performance and enhance results, all while refraining from questioning the existing practices that govern these activities (Orderud and Winsvold, 2012; Pahl-Wostl, 2009; Wulandhari *et al.*, 2021). In this case, the improvement is only at cognitive level such as refined skills, techniques and knowledge using established norms (King *et al.*, 2023; Wulandhari *et al.*, 2021). Double loop learning, is an advanced form of learning that emphasizes the importance of questioning and reflecting on actions in order to reframe and facilitate change (Pahl-Wostl, 2009). At this learning level, there is adjustment and reinterpretation on assumptions, value, norms, perspectives, protocols (King *et al.*, 2023; Orderud and Winsvold, 2012). The refinement of mental models has the potential to catalyze broader systemic transformations, especially in the context of triple loop learning. Pahl-Wostl (2009) contended that double loop learning is only effective if continued with triple loop learning as it represents actual actions as the embodiment of affective or mental model adjustment and reinterpretation. Thus, triple loop learning pertains to the tangible application of establishing new norms, roles, protocols, and networks, indicative of institutional and structural changes that promote a paradigm shift (King *et al.*, 2023; Orderud and Winsvold, 2012). The process of multi loop learning can be described in Fig. 1.

The study aimed to analyse the possibility of social learning and CoP implementation to improve public community participation in waste management system using literature review study approach, with social learning and multi loop learning theory as the theoretical baseline. This study undertook various methodological steps to achieve its research aims. The initial phase focused on delineating the expected characteristics of learning-based interventions that could enhance public participation in civil society, based on findings from previous studies. Second, it was identified existing learning-based interventions which were commonly applied or suggested by previous studies to improve public participation and evaluate their abilities to meet the requirements. The purpose of these two analyses was to establish a hypothetical baseline indicating that social

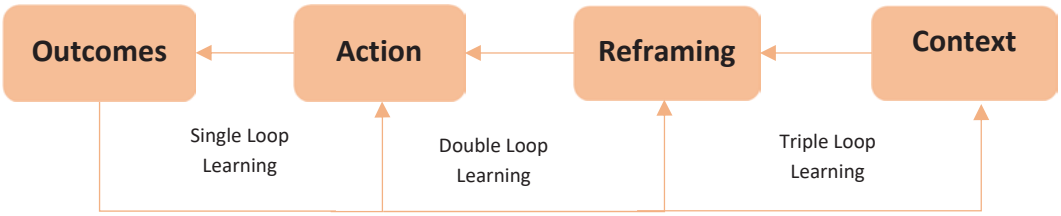


Fig. 1: Multi Loop Learning Theory (Hargrove, 2002; Pahl-Wostl, 2009)

learning can fulfill the intervention requirements when compared to alternative intervention strategies. Third, it was identified the existing CoP implementation and the learning outputs/outcomes which provide practical and empirical evidence for its implementation in waste management context. Lastly, it was proposed CoP model and its multi loop learning model as conceptual benchmark for CoP implementation in waste management context. This review study has been carried out in Indonesia in 2024.

METHODOLOGY

This study used literature review study approach to answer the research question. The literature review contains 5 main steps: Formulating review questions, searching literature comprehensively through Scopus database with inclusion and exclusion criteria, screening, assessing and extracting, synthesizing and interpretation (Davis *et al.*, 2014).

Data collection

The selected literature comprises only those papers published up to the year 2023, as indexed in the Scopus Database. The methodology for selecting the literature is illustrated in Fig. 2.

The application of inclusion and exclusion criteria guided the selection of literature for the review process. In this study, there are two types of inclusion criteria to choose studies with the topic about waste management and studies with CoP topic. A comprehensive manual screening and detailed review of the articles were conducted, concentrating on the title, abstract, and full text, in accordance with the predetermined inclusion and exclusion criteria. The parameters for the inclusion and exclusion

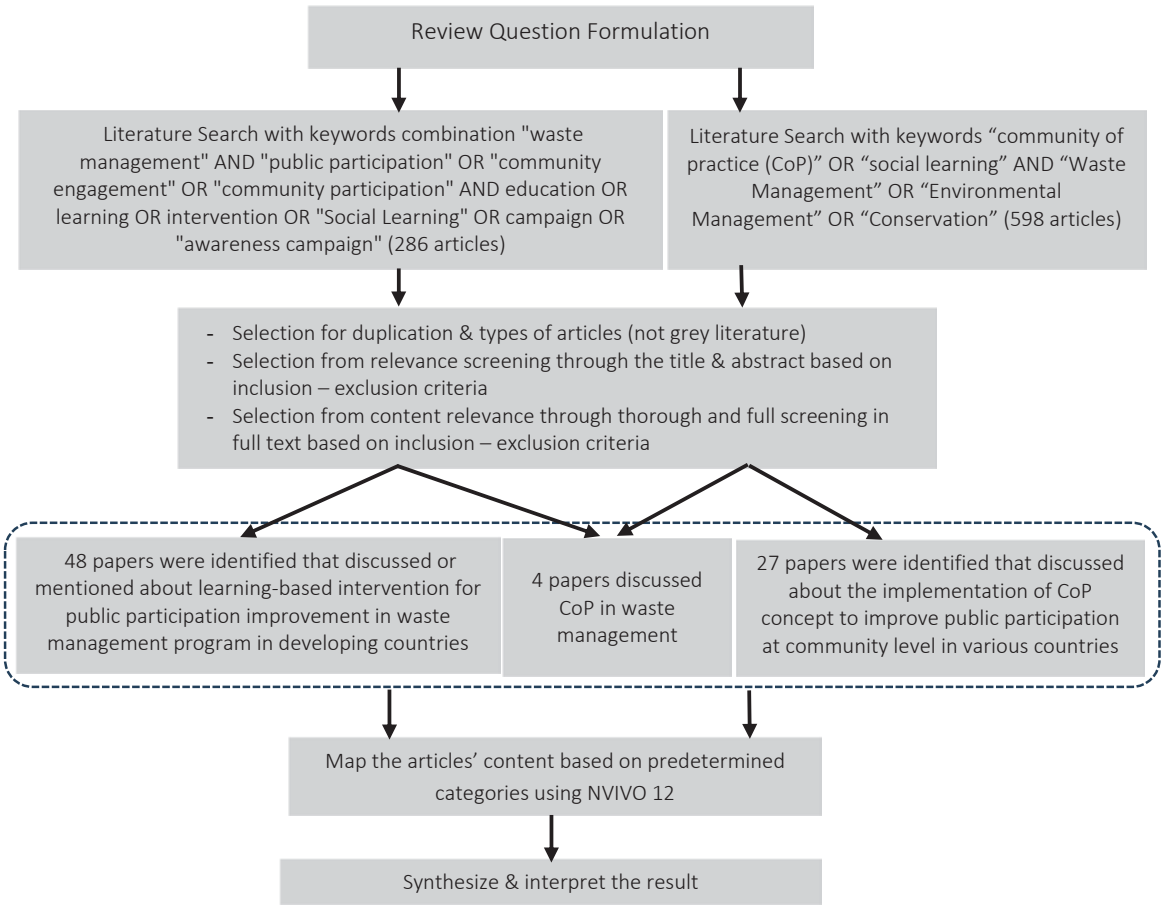


Fig. 2: Literature review search methodology

of research pertaining to waste management are detailed as follow: 1) The literature should discuss, mention or suggest about learning-based intervention on the body text; 2) This learning-based intervention seeks to bolster community involvement in the waste management frameworks within developing countries; 3) The studies without specific discussion on public participation improvement and learning-based intervention suggestion is excluded from the review. Meanwhile, the inclusion and exclusion criteria for CoP are as follow: 1) The literature should discuss about CoP and or social learning that involved public society or local communities in the CoP; 2) Or the CoP being discussed is related to environmental conservation or environmental management domain, even though the CoP is not involved local communities at all; 3) CoP can be both from developed or developing countries; 4) If there is no mentioning CoP or social learning, the studies is excluded from the review; 5) If the CoP is purely profession-based without involving local communities or is intra-organization (formal) or purely virtual CoP, the study is excluded. The examination of CoP extended beyond developing countries, given that there is still a significant deficiency in research addressing the role of CoP in improving public participation within these contexts. Therefore, the selection is expanded to get more comprehensive insights about CoP implementation. Articles that fulfilled the criteria for both topic keywords but lacked accessible full texts were also excluded from consideration. To enhance the breadth of pertinent literature, the search strategy was broadened by examining the references cited in the selected papers, thereby identifying additional relevant studies.

Data extraction

After a thorough and careful review, the final selected papers in total are 52 papers related to waste management and learning-based intervention strategy topic, and 31 papers related to CoP implementation in community and or with the domain environmental management and conservation domain. A total of four papers were identified that pertain to both subjects, focusing on waste management and the implementation of its CoP. A thorough reading of all papers was performed, and coding was executed utilizing NVIVO 12 tool. The coding was categorised into several themes as presented in Fig. 3.

The process of content coding involved a comprehensive review of all selected articles, systematically categorizing the content according to established criteria. In prior research concerning waste management, the primary focus of the search was about: 1) the research findings that explicitly or clearly stated about the expected characteristics of learning-based intervention to improve public participation; 2) type of learning-based intervention strategies mentioned by the studies. Subsequently, each category of interventions was organized and classified according to shared characteristics, and an evaluation was conducted based on the attributes identified in the 1th point. For CoP studies, the main searching is about: 1) the CoP identity including its name and domain, CoP members, learning activities and output or outcome of the CoP activities. 2) CoP level was determined based on the variety of members involved, while the learning level and learning type were categorised based on the concept of multi loop learning theory.

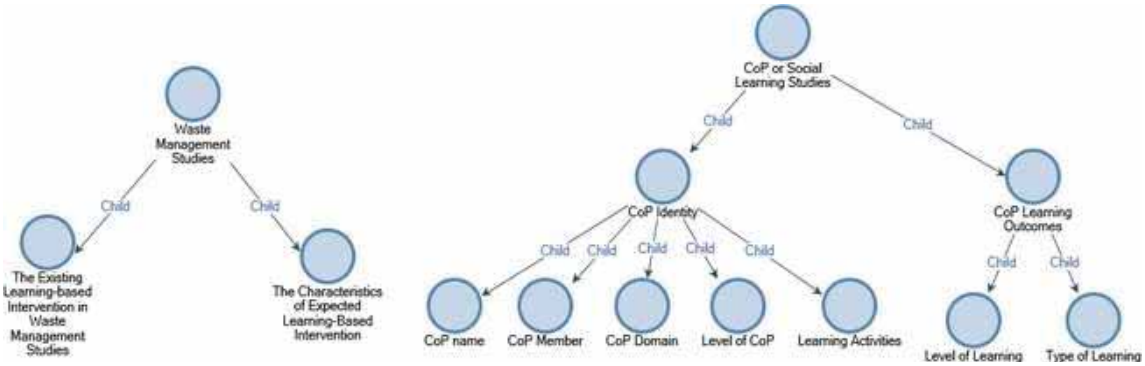


Fig. 3: Coding categories for data extraction process

DISCUSSION

Through the screening and selection of the papers regarding the given keywords, it was selected 52 papers mentioning, discussing or suggesting types of learning-based interventions on waste management program and 31 papers discussing about the implementation of CoP concept to improve public participation at various level including civil society in various countries. Table 1 presents a comprehensive list of all the selected papers.

Table 1: The selected papers suggesting learning-based intervention on waste management program

No.	Sources	Country	No.	Sources	Country
1	Johnson and Wilson, 2000	Zimbabwe	27	Ulhasanah and Goto, 2018	Indonesia
2	Premakumara *et al.*, 2011	Indonesia	28	Wang *et al.*, 2018	China
3	Sari and Umanto, 2013	Indonesia	29	Xu *et al.*, 2018	China
4	Idamah, 2015	Nigeria	30	Pei, 2019	China
5	Navykarn and Muneenam, 2015	Thailand	31	Gyimah *et al.*, 2019	Ghana
6	Tiew *et al.*, 2015	Malaysia	32	Liu *et al.*, 2019	China
7	Mamady, 2016	Guinea	33	Singer *et al.*, 2019	Vietnam and Indonesia
8	Mukama *et al.*, 2016	Uganda	34	Chen and Gao, 2020	China
9	Oduro-Kwarteng *et al.*, 2016	Ghana	35	Chikowore, 2020	Zimbabwe
10	Ramadan *et al.*, 2016	Indonesia	36	Knickmeyer, 2020	Literature Review
11	Song *et al.*, 2016	China	37	Limon *et al.*, 2020	Philippines
12	Yeh *et al.*, 2016	Taiwan	38	Sekito *et al.*, 2020	Indonesia
13	Yuan *et al.*, 2016	China	39	Wang *et al.*, 2020	China
14	Chow *et al.*, 2017	China	40	Zheng *et al.*, 2020	China
15	Elayan and Ibrawish, 2017	Jordan	41	Ghazali *et al.*, 2021	Indonesia
16	Loan *et al.*, 2017	Vietnam	42	Jiang *et al.*, 2021	China
17	Trihadiningrum *et al.*, 2017	Indonesia	43	Lissah *et al.*, 2021	Ghana
18	Xu *et al.*, 2017	China	44	Odhiambo *et al.*, 2021	SSA Countries
19	Yukalang *et al.*, 2017	Thailand	45	Pierini *et al.*, 2021	Argentina
20	Fredrick *et al.*, 2018	Uganda	46	Sunarti *et al.*, 2021	Literature Review
21	Liao *et al.*, 2018	China	47	Bonatti *et al.*, 2022	Brazil
22	Lee *et al.*, 2019	China	48	Cishahayo *et al.*, 2022	China
23	Ma *et al.*, 2018	China	49	Sayara *et al.*, 2022	Palestine
24	Maryati *et al.*, 2018	Indonesia	50	Nepal *et al.*, 2023	Nepal
25	Ddiba *et al.*, 2020	Kenya	51	Atta *et al.*, 2023	Ghana
26	Padilla and Trujillo, 2017	Columbia	52	Sunarti *et al.*, 2023	Indonesia

Selected articles on the topic of CoP

No.	Sources	Country	No.	Sources	Country
1	Johnson and Wilson, 2000	Zimbabwe	17	Didham *et al.*, 2017	Oklahoma, Japan
2	Measham, 2009	Western Australia	18	Granadino, 2017	Peru
3	Beynen and Fleury, 2010	Florida, USA	19	Kim, 2017	London
4	Morgan, 2011	Wales	20	Mehring *et al.*, 2018	England
5	Meessen *et al.*, 2011	Burundi	21	Tran *et al.*, 2018	Vietnam
6	Goven *et al.*, 2012	New Zealand	22	Triste *et al.*, 2018	Europe
7	Raymond and Robinson, 2013	South Australia	23	Essen *et al.*, 2019	Europe
8	Maiello, 2014	Brazil	24	Jordan *et al.*, 2020	Belize, Central America
9	Reed *et al.*, 2014	Canada	25	Vetter, 2020	UK
10	Nykvist, 2014	Sweden	26	Odhiambo *et al.*, 2021	SSA Countries
11	Bradbury and Middlemiss, 2015	England	27	Wulandhari *et al.*, 2021	Indonesia
12	Noguera-Méndez *et al.*, 2016	Cuba	28	Bonatti *et al.*, 2022	Brazil
13	Benítez *et al.*, 2020	Cuba	29	Ghazali *et al.*, 2021	Indonesia
14	Binot *et al.*, 2015	Thailand, Laos, Cambodia	30	Sunarti *et al.*, 2023	Indonesia
15	Dolinska, 2016	North West Tunisia	31	King *et al.*, 2023	UK
16	Montero, 2016	Brazil			

Learning-based intervention expectation in waste management program

Learning approach has been discussed and mentioned by abundance of previous studies in the context of waste management. A set of criteria has been proposed to enhance learning strategies that can effectively influence behavioral changes in society, especially within low- and middle-income countries. Various studies have proposed alternative methodologies that could be adopted in order to enhance the effectiveness of the approach. For instance, Mamady (2016) and Padilla and Trujillo (2017) recommended employment of multiple media, including internet, while Wang *et al.* (2018) advocated posters and social media utilization to reach a wider range of population in knowledge dissemination. While employing media for educational purposes can effectively engage a larger demographic, it may not yield significant results as it often lacks a concentrated approach to the education of particular communities. Typically, such contents only grab people who concern on the topic while people with less or no awareness and negative attitude toward waste management may avoid the contents because it does not align with their preferences. It implies that there is no learning happened unless there is self-active learning intention from the audience. According to the findings of Zheng (2020), it is evident that media publicity has a limited impact, suggesting that broad publicity does not serve as a viable solution. It may because media publicity only facilitates one-way communication, and does not allow face to face interaction which is direct and intensive for effective knowledge internalization and communication strategies (Knickmeyer, 2020; Sunarti *et al.*, 2023). Some studies also suggested local community problem adjustment to nurture good engagement and trust to increase social connectivity which can be facilitated by social learning 23). A number of studies adopt diverse terminology to define social connectivity in local communities, using phrases such as neighbourhood ties, community attachment, and social connections (Pei, 2019; Zheng *et al.*, 2020). Developing engagement and trust requires continuous activity, denoting long period of social learning activities (Knickmeyer, 2020; Loan *et al.*, 2017; Mehring *et al.*, 2018; Oduro-Kwarteng *et al.*, 2016; Yeh *et al.*, 2016). As short-term social connection was failed to give significant impact to the community change (Xu *et al.*, 2018). The establishment of trust among individuals within the community and across different sectors is crucial, as insufficient trust can impede the advancement of collaborative initiatives related to waste management, whether these initiatives stem from local governmental bodies or the community at large (Bonatti *et al.*, 2022). It implied the requirements of an integrated, long-term, and structured learning system to be conducted focusing on specific community to reach sustainable waste management (Knickmeyer, 2020; Pei, 2019; Zheng *et al.*, 2020). Chikowore (2020) added key actor involvement to be another criterion for a learning-based intervention in waste management system as they take a role as a change driver in the community, meaning that they become the key actor to influence the whole community to change their old habits. Facilitating learning-by-doing is also suggested by some studies (Ghazali *et al.*, 2021; Knickmeyer, 2020; Liao *et al.*, 2018; Sunarti *et al.*, 2023; Xu *et al.*, 2017; Yeh *et al.*, 2016), as direct practice is vital to enable habituation (Zebua and Sunarti, 2021) which eventually leads to transformative change on their habits toward waste management. The learning-by-doing approach may answer the requirement of establishing new waste management culture as suggested by Knickmeyer (2020), Liao *et al.* (2018) and Xu *et al.* (2017). Ultimately, studies focused on abundance have revealed the significance of affective and psychological elements in fostering enduring behavioral changes among individuals. (Chen and Gao, 2020; Knickmeyer, 2020; Lissah *et al.*, 2021; Liu *et al.*, 2019; Pierini *et al.*, 2021; Sayara *et al.*, 2022; Sunarti *et al.*, 2021; Wang *et al.*, 2018). Consequently, the educational activities must promote a minimum of twofold learning at the individual level to encourage mindful behavioral change (King *et al.*, 2023; Orderud and Winsvold, 2012; Pahl-Wostl, 2009). Hence, it is concluded that the characteristics of expected learning-based intervention to improve public participation is as shown in Table 2.

Existing learning-based intervention strategies from previous studies

A comprehensive literature review encompassing 52 prior studies focused on public participation in waste management systems within developing countries has led to the identification of several learning-based intervention programs, which are summarized in Table 3. Each type of learning-based intervention

Table 2: Requirement of learning strategies for effective encouragement of public participation in waste management system according to previous studies

No.	Requirements	Sources
1	Provide social learning to facilitate social interaction and collective learning to facilitate two-way communication	Bonatti *et al.*, 2022; Cishahayo *et al.*, 2022; Ddiba *et al.*, 2020; Ghazali *et al.*, 2021; Mehring *et al.*, 2018; Pei, 2019; Sunarti *et al.*, 2023; Zheng *et al.*, 2020
2	Durable education program for continuous learning (long term)	Knickmeyer, 2020; Loan *et al.*, 2017; Mehring *et al.*, 2018; Oduro-Kwarteng *et al.*, 2016; Xu *et al.*, 2018; Yeh *et al.*, 2016
3	Employment of informative and intensive campaigns	Mamady, 2016; Padilla and Trujillo, 2017; Wang *et al.*, 2018; Zheng *et al.*, 2020
4	Integrated and structured learning system focused on specific community	Knickmeyer, 2020; Pei, 2019; Sayara *et al.*, 2022; Zheng *et al.*, 2020
5	Key actors' involvement as agent of change	Chikowore, 2020
6	Learning by doing encouragement to build habits (Practice)	Knickmeyer, 2020; Liao *et al.*, 2018; Sunarti *et al.*, 2023; Xu *et al.*, 2017; Yeh *et al.*, 2016
7	Develop new culture of waste management	Knickmeyer, 2020; Liao *et al.*, 2018; Xu *et al.*, 2017
8	Nurture affective or psychological factors	Chen and Gao, 2020; Knickmeyer, 2020; Lissah *et al.*, 2021; Liu *et al.*, 2019; Pierini *et al.*, 2021; Sayara *et al.*, 2022; Sunarti *et al.*, 2023; Wang *et al.*, 2018

strategy was grouped into several categories based on their common characteristics: paper-based learning approach, virtual-based learning approach, learning by doing approach and social learning approach. Subsequently, each category of learning approach is examined and aligned with the anticipated learning strategies that were outlined earlier and illustrated in Table 2.

Based on the results illustrated in Table 3, it appears that numerous existing strategies do not fulfill the necessary conditions for effective intervention when executed independently. Paper-based and virtual-based learning approach, both cannot focus on specific community because it is massive campaign that purely depend on individual intentions whether they want to learn or not from the contents being shared (e.g., posters, newspaper, TV/radio programs, etc). Consequently, the extent to which the learning loop can manifest, whether in the context of single-loop or double-loop learning, remains indeterminate. This variability is fundamentally contingent upon the individual's commitment to engaging with the learning process. Both approaches were also only one-sided learning, so that it is most likely no social interaction to occur causing low possibility to build trust and bonding among social community, which is vital to enable collaboration in waste management system (Bonatti *et al.*, 2022; Ramadan *et al.*, 2016). Learning by doing approach is powerful to facilitate single loop learning at individual level as it allows individuals to learn directly the practical skill to conduct waste management activities. The formation of new habits is achievable; however, it often occurs without a thorough examination of their effectiveness. At the individual level, double-loop learning can be facilitated when individuals engage in critical reflection regarding their actions (Sunarti *et al.*, 2023). However, the chance to allow triple loop learning to build trust, new norm and culture toward waste management is low unless this learning approach is embedded in more structured program such as CoP (Bonatti *et al.*, 2022) or Citizen science (Pierini *et al.*, 2021). Social learning approaches can be classified into several categories, with a notable distinction based on the length of the program, leading to two specific types. Some social learning types typically occur temporarily such as public campaign, doorstep campaign, workshop/seminar, training/mentoring/courses which were commonly conducted within days or months. Typically, citizen science, organized social learning initiatives, and communities of practice demonstrate enhanced longevity over several years. The duration of these programs plays a crucial role in shaping outcomes, both on an individual and collective level, by allowing for more intensive interactions and extended opportunities for practical engagement. Thus, these three types of intervention tend to nurture affective factor at individual and social level, and develop new culture as a result of triple loop learning (Pahl-Wastl,

Table 3: Existing learning-based intervention strategies to encourage public participation

Sources	Learning-based intervention strategies	Characteristics							
		Social interaction	Durability	Intensive campaigns	Specific community	Practice	Agent of change	New culture development	Nurture affective factor
Paper-based learning approach									
Fredrick *et al.*, 2018; Nepal *et al.*, 2023; Ramadan *et al.*, 2016; Zahra *et al.*, 2012	Posters/banners/ pamphlets								
Chow *et al.*, 2017; Fredrick *et al.*, 2018; Idamah, 2015; Mamady, 2016; Song *et al.*, 2016; Yuan *et al.*, 2016	Newspaper	No	No	No	Depend	No	No	No	Depend
Chow *et al.*, 2017; Limon *et al.*, 2020; Wang *et al.*, 2020	Handbooks/manual books								
Virtual-based learning approach									
Chow *et al.*, 2017; Fredrick *et al.*, 2018; Idamah, 2015; Liao *et al.*, 2018; Ma *et al.*, 2018; Song *et al.*, 2016; Wang *et al.*, 2020; Yuan *et al.*, 2016	TV/radio programs								
Jiang *et al.*, 2021; Knickmeyer, 2020; Ramadan *et al.*, 2016; Sayara *et al.*, 2022; Ulhasanah and Goto, 2018	Website/social media	Depend	Depend	Depend	No	No	No	Depend	Depend
Wang *et al.*, 2020	Mobile apps								
Learning by doing based approach									
Lee *et al.*, 2019; Wang *et al.*, 2020	Environmental competition	Yes	Short-term	No	No	Yes	Depend	No	Depend
Ghazali *et al.*, 2021; Limon *et al.*, 2020; Premakumara *et al.*, 2011; Sunarti *et al.*, 2023; Trihadiningrum *et al.*, 2017; Yeh *et al.*, 2016; Zahra *et al.*, 2012	Practicing	Depend	Depend	Yes				Depend	
Social learning-based approach									
Lee *et al.*, 2019; Liao *et al.*, 2018; Mukama *et al.*, 2016; Ramadan *et al.*, 2016; Sekito *et al.*, 2020; Singer *et al.*, 2019; Song *et al.*, 2016; Tiew *et al.*, 2015; Xu *et al.*, 2018	Public campaign/ movement/event/ doorstep campaign	Yes	Short-term	Yes	Depend	Depend	Depend	Depend	Depend
Cishahayo *et al.*, 2022; Elayan and Ibrawish, 2017; Limon *et al.*, 2020; Nepal *et al.*, 2023; Ulhasanah and Goto, 2018	Workshop/seminar		Short-term	Yes	Specific		Yes	No	
Atta *et al.*, 2023; Cishahayo *et al.*, 2022; Gyimah *et al.*, 2019; Lee *et al.*, 2019; Limon *et al.*, 2020; Maryati *et al.*, 2018; Navykarn and Muneenam, 2015; Sari and Umanto, 2013; Sayara *et al.*, 2022; Singer *et al.*, 2019; Wang *et al.*, 2020; Yukalang *et al.*, 2017	Training/mentoring/ course		Short-term	Yes	Yes	Yes	Yes	No	
Pierini *et al.*, 2021	Citizen Science		Long-term	Yes	Yes	Yes	Yes	depend	Yes
Chow *et al.*, 2017; Ddiba *et al.*, 2020; Premakumara *et al.*, 2011; Singer *et al.*, 2019; Trihadiningrum *et al.*, 2017; Zahra *et al.*, 2012	Structured Social Learning Program	Yes	Long-term	Yes	Yes	Yes	Yes	Yes	Yes
Bonatti *et al.*, 2022; Ghazali *et al.*, 2021; Johnson and Wilson, 2000; Sunarti *et al.*, 2023;	CoP	Yes	Long-term	Yes	Yes	Yes	Yes	Yes	Yes

2009). However, citizen science approach is highly focused on research-based activities, suggesting collaborative parties mostly from researchers and academia in addition to government parties, while structured social learning program can avoid focused group of society and collaborating members as there is no membership inside the program. The partnership exhibited an inherent imbalance, with civil society being positioned as the subject of the program, while government agencies assumed the role of authority (Premakumara *et al.*, 2011; Singer *et al.*, 2019; Trihadiningrum *et al.*, 2017; Zahra *et al.*, 2012). Meanwhile, CoP offers collaborative partnership among involved parties across sectors, organizations and level who can be the members, including individuals from civil society and community group. Thus, the risk of unfriendly situation, incoordination and dominance of government roles can be decreased (Zhang and Zhu, 2022; Ain *et al.*, 2020).

CoP on existing social learning-based initiatives

An extensive examination of 31 articles revealed the presence of 29 CoP across diverse domains and levels. Comprehensive details regarding the identified CoP from the reviewed literature are summarized in Table 4.

As illustrated in Table 4, the findings reveal that the scope of the Community of Practice (CoP) is characterized by its variability and flexibility. It can be in the area of skill improvement on hobby (Essen *et al.*, 2019), skill and value creation for business improvement on various field (Benítez *et al.*, 2020; Morgan, 2011; Nykvist, 2014; Raymond and Robinson, 2013; Tran *et al.*, 2018; Triste *et al.*, 2018; Vetter, 2020; Wulandhari *et al.*, 2021), including environmental management and conservation improvement to achieve collective behavioral change at individual and community levels (Beynen and Fleury, 2010; Bonatti *et al.*, 2022; Didham *et al.*, 2017; Ghazali *et al.*, 2021; Kim, 2017; Measham, 2009; Sunarti *et al.*, 2023) or organizational levels (Binot *et al.*, 2015; Goven *et al.*, 2012; Granadino, 2017; King *et al.*, 2023; Maiello, 2014; Meessen *et al.*, 2011; Mehring *et al.*, 2018; Montero, 2016; Reed *et al.*, 2014). In term of members' variety, it seems that CoP platform can be implemented at every level of communities, from individuals in a local group of community (Essen *et al.*, 2019; Jordan *et al.*, 2020; Tran *et al.*, 2018) to a group of multi-level across organizations (Didham *et al.*, 2017; Johnson and Wilson, 2000; Maiello, 2014) or across regions (Measham, 2009). The roles and profession are also varied, from the individual interest (Essen *et al.*, 2019) to nation-development program planning (Beynen and Fleury, 2010; Goven *et al.*, 2012; Maiello, 2014; Measham, 2009; Reed *et al.*, 2014) or even collaborative program across nation (Binot *et al.*, 2015; Odhiambo *et al.*, 2021; Triste *et al.*, 2018). The roles of the members can also be varied from the civil society as the grassroots party, community groups, environmentalists, NGOs, business-based organizations and also local and regional government agencies, with the focus on facilitation of intensive interaction in formal and causal ways, joint activities either communal or individuals and even collaborative projects to reach shared goals from the CoP. Due to the complexities inherent in social learning activities designed for a varied group of individuals, multi-loop learning can take place at every hierarchical level.

The characteristics of cop learning activities

Previous studies have identified several characteristics of learning activities that are enhanced through the CoP approach. First, CoP facilitates experiential and communication-based learning activities such as participatory learning process, project collaboration, training and workshops as found in several CoPs in Table 4. Engaging in such learning activities promotes the dissemination of tacit knowledge pertinent to the area of focus (Tran *et al.*, 2018). In the domain of agricultural and livestock farming for example, the farmers require local knowledge gathered from elders' experience in dealing certain situation related to the nature, landscape, and so forth, which cannot be found through formal learning (Vetter, 2020). Through direct experience and active engagement, the farmers gained insights from older relatives, neighboring individuals, and other members of the community who had dealt with comparable challenges (Tran *et al.*, 2018). Similarly, Ddiba *et al.* (2020) contended that CoP bridge the gaps between theoretical concept of circular economy toward waste management and local knowledge and cultural norms owned by public community related to how they treat organic waste for recycle and recovery. The CoP serves as a platform that facilitates interaction among local stakeholders and individuals from

Table 4: CoP Implementation in the domain related to Environmental Management and Conservation

No.	CoP name	Country	Domain	Members	Level of CoP	Goals	Learning activities	Sources
1	Environmental action group (EAG)	Zimbabwe	Waste issue	Government, Local NGO, voluntary association	Multi-level across organization	To resolve urban solid waste problems in local areas in Zimbabwe, specifically recycling project	Participatory process, workshops involving experts, partnership	Johnson and Wilson, 2000
2	Catchment demonstration initiative (CDI)	Western Australia	Salinity management	Community residents, local managers, Landholders, researchers (invited)	Multi-Level across region	To assist building farmers' capacity for best salinity management practice	Participatory demonstration projects	Measham, 2009
3	Karst community/Karst information portal (KIP)	West Central Florida, USA	Karst and cave conservation	Formal researchers, caving enthusiasts, government agencies	Multi-level across organizations and individuals	To foster interaction and collaboration among the karst community	Participatory process by caving together, meeting, surveying new caves, cave exhibition,	Beynen and Fleury, 2010
4	- Organic meat farmer-led marketing group - Organic meat farmer discussion group	Wales	Organic meat production	- Long-term full-time beef and lamb farmers - Dairy, beef, and lamb farmers	Local individuals and group communities	- Collaborative marketing channel - To improve organic production and knowledge management	Discussion group, individual irregular interaction, neighborhood meetings, regular discussion, Intermittent one-on-one discussion	Morgan, 2011
5	Performance-based financing (PBF) CoP	Burundi	Sustainable finance on health care	Experts on implementing or assessing PBF	Multi Professional-based community	To consolidate the body of knowledge on PBF through good practices identification and Health Care financing dissemination	e-discussion, face to face events, Workshops, training and courses	Meessen *et al.*, 2011
6	Long term council community plans (LTCCP)	New Zealand	Biosolids Management	Local government councils, iwi (Maori local community)	Government and local community	To involve community in planning and making decision for environmental, economic and social development, especially in Biosolids Management	Consultation, public meetings; personalized letters; newsletters or magazines, newspaper articles, leaflets, and written reports; school tours of treatment plants	Goven *et al.*, 2012
7	Farm system group	South Australia	Climate Change on Farming System	Farmers, farm consultants and agronomists	Profession-community group, professionals	Adaptation to short- term risks of climate change to farming system	Monthly meeting, learning by doing, informal interaction between communities; farming collaboration	Raymond and Robinson, 2013
8	Iguacu project	Rio De Jeniero, Brazil	Flood Management	Local Residents, Local Committee, Local Governments, NGOs	Multi-Level Across organization	To prevent recurrence of the factors of environmental imbalance, leading to flood	Participatory Process	Maiello, 2014
9	Canadian Biosphere Reserve Association (CBRA)	Canada	Biological conservation	Government, Scientists, Researchers, Practitioners, academics, Community resident	Multi-Level (Multi organizations, professionals and local communities)	Biological conservation, advance sustainability, learning and public education, support scientific research	Participatory process in projects, face to face meeting, workshops, learn peer to peer learning	Reed *et al.*, 2014

Continued Table 4: CoP Implementation in the domain related to Environmental Management and Conservation

No.	CoP name	Country	Domain	Members	Level of CoP	Goals	Learning activities	Sources
10	Modern farming CoP	Sweden	Environmental-economic natural resource management	Large-scale agricultural farmers, family and farming employees, advisors, consultants	Business Professionals	To better manage and govern natural resources in the modern agricultural sector with environmental-economic trade off	Regular informal meeting, workshops	Nykvist, 2014
11	Green action	Yorkshire, England	Sustainable consumption	Student volunteers from Leeds University students' union	Students	To share skill and knowledge about sustainable consumption	Regular meeting, interaction among members, participatory process on food hub, discussions,	Bradbury and Middlemiss, 2015
12	PIAL (Participatory seed diffusion program)	Cuba	Local productive farming sustainability	Farmers, technicians, scientists across municipalities and provinces	Multi local and national communities	Promote prolonged changes in local productive farming systems for economic, social and environmental benefits to the community	Participatory process; Capacity building workshops; other Farm visiting	Benítez *et al.*, 2020; Noguera-Méndez *et al.*, 2016
13	One health	Thailand, Laos, Cambodia	Human, animal, environment interface	Researchers, Policymakers, public health and veterinarian officers, social and ecological scientists, agriculture workers	multi-stakeholders and cross-sectoral	Addressing specific issues related to human, animal and environment interface	Experiential learning, collaborative field-based work., training,	Binot *et al.*, 2015
14	Agricultural innovation	North West Tunisia	Climate Change on agricultural Farming	Dairy farmers in 3 innovation projects	Professional Farmers	Conservation agriculture targeting cereal production in different climatic zones	Regular meeting, Discussion	Dolinska, 2016
15	Cidade do Saber (CDS)/The city of knowledge	Brazil	Construction citizenship	Academia, teachers, politicians (administrators and instructors)	Municipal level	To promote access to cultural, sport and educational goods, for excellent citizenship construction	Collaboration, discussion, interaction	Montero, 2016
16	The Okayama education for sustainable development (ESD)	Oklahoma, Japan	Sustainable society development	Schools, community learning center (kominkans), NGOs and universities	Multi organizations	to create a community that learn, think and act collectively to achieve a sustainable society	Discussion, practice, participatory action research	Didham *et al.*, 2017
17	Planning for climate change in (PlanCC Project)	Peru	Low-emission national development plan for climate change	Ministries, Research institution, consultancy team, academics	National Level	To included climate change variable into consideration in development plan to achieve low-emission	Discussions, training, project collaboration, constant meetings, presentation,	Granadino, 2017
18	London community gardeners	London	Behavioral change on food and food waste management	Local communities	Gardening Enthusiasts (individuals) and garden Community Group	Promote behavioral change for foodprint reductions, specifically, changing individual food consumption behaviors including food waste management behavior.	Experiential Learning; Community interaction	Kim, 2017
19	Flood communities	England	Flood risk management	Local Communities	Community level	To manage flooding risk	Knowledge gathering, Conference, workshops, forum	Mehring *et al.*, 2018

Continued Table 4: CoP Implementation in the domain related to Environmental Management and Conservation

No.	CoP name	Country	Domain	Members	Level of CoP	Goals	Learning activities	Sources
20	Vietnamese metkong delta (VMD)	Vietnam	Farming and environmental conservation	Agricultural farming households, local Farmer association	Individuals and Community group	To exchange practical experience and knowledge, solve problems related to farming, local flood management policies, climate change and upstream hydropower development	Casual gatherings, FGD, regular interaction, peer to peer experiential exchange at daily interaction, farm visits, collaboration	Tran *et al.*, 2018
21	Flanders (Belgium) and Northern Ireland (UK).	Europe	Value creation on dairy farming sustainability	Dairy farmers, research institutions, advisory services and policy makers, experimental farms or agricultural schools	Regional level	To improve value creation on dairy farming for sustainability	Regional farmer group meetings, farm visits, exchange visits, trainings, demonstrations, Perform and disseminate technical research, on-farm research, project collaboration, informal interaction	Triste *et al.*, 2018
22	No specific name (Hunter CoP)	Denmark, UK, Netherland, Sweden, Germany	Hunting Skill	Hunters with specific interest/characteristics based on domain	hobby-based Community	Game, Landscape, Weapon, Resident-based, Method, Style, Motivation, Class, Organization, Temporality	Direct communication, interaction, observation to other members	Essen *et al.*, 2019
23	Potter community Belize river valley	Belize, Central America		Maya potters (mostly households)	Profession-based Community	Share experience and knowledge about local landscape, raw material properties, production process, clay selection, fire and decoration	Imitation, direct observation to other members, face-to-face interaction,	Jordan *et al.*, 2020
24	Pasture-fed livestock association (PFLA)	UK	Sustainable agri-food management	Livestock farmers, certified organic meat producers, far butchers, consumers	Individuals, community group, Profession-based community	To promote sustainable agri-food system that are environment-friendly, biodiversity, healthy product	Peer to peer learning (Online forum), annual meeting, Conference, study tour, farm walks, engagement in research project, training, seminars, workshops	Vetter, 2020
25	LabCoP	Sub-Saharan African Country	Hazardous waste management	National stakeholders, clinicians, laboratorians, community residents	Multi-national level	to support joint knowledge creation and quick adoption of ideas to hazardous waste management (HIV waste)	Face to face meeting, structured discussion, country visit, webinar sessions, informal dialogue	Odhiambo *et al.*, 2021
26	Sekolah Peternakan Rakyat (SPR)/farmer breeder school	Indonesia	Farming upscaling	Researchers, cattle farmers, local government, NGO	Profession-based community group	To educate small-scale cattle farmers to be independent farmers and own a business	Participatory learning, weekly meeting, casual daily interaction, collaboration	Wulandhari *et al.*, 2021
27	Bucket Revolution Project (BRP)	Brazil	Public participation in waste management	Residents, NGOs, University students	Across community level	An initiative to encourage active participation of residents in separation and collection of organic waste from households to collective recycling at the local public school	Direct learning, Participatory process, collective learning, knowledge sharing activities to other communities, workshops	Bonatti *et al.*, 2022

Continued Table 4: CoP Implementation in the domain related to Environmental Management and Conservation

No.	CoP name	Country	Domain	Members	Level of CoP	Goals	Learning activities	Sources
28	Kawasan Bebas Sampah (KBS)/zero waste area	Indonesia	Public participation in waste management	Residents, NGOs, Local Government, waste Management Officers	Community Level and across community level	To educate and encourage active participation of resident in communal waste management program (waste recycle, separation, waste recovery)	Direct learning, Participatory process, knowledge sharing activities to other communities, trainings, workshops	Ghazali *et al.*, 2021; Sunarti *et al.*, 2023
29	iCASP Yorkshire NFM CoP	UK	Natural Flood Management	local authorities, environmental and conservation organisations, water utilities, and academics	Multi Organization	To enable monitoring, modelling capabilities, resource exchange, collaboration and coordination between practitioner groups and community toward Natural Flood Management (NFM)	Quarterly meeting, Events, site visits, themed workshops	King *et al.*, 2023

various roles, allowing them to exchange diverse perspectives and cultural norms pertinent to their respective fields (Fulgenzi *et al.*, 2020). Beside practice-based, CoP becomes a social learning framework that enables intensive communication-based learning activities such as peer to peer casual discussion, group discussion, casual interactions as well as collaborative project work that facilitate both long-term practice-based and communication-based learning which are important to facilitate and triple loop learning (Beattie *et al.*, 2022; Fulgenzi *et al.*, 2020; Ghazali *et al.*, 2021; King *et al.*, 2023; Sunarti *et al.*, 2023). The combination of casual and intensive interactions promotes the development of close relationships among members, which is vital for facilitating the transfer of tacit knowledge from the knowledge owner to others. Consequently, this bonding emerges as a fundamental factor influencing the success of knowledge-sharing initiatives (Reed *et al.*, 2014; Tran *et al.*, 2018; Vetter, 2020). Due to its membership system, the learning activities can focus on the members in the group or community so that it can intensively engage and empower its community bonding and among community members as it occurs within a long duration (Mehring *et al.*, 2018; Morgan, 2011; Reed *et al.*, 2014; Tran *et al.*, 2018). Despite the membership structure inherent in CoP, it is permissible to invite external experts to contribute specialized knowledge as needed, a practice observed in certain CoPs (Ghazali *et al.*, 2021; Johnson and Wilson, 2000; Meessen *et al.*, 2011; Triste *et al.*, 2018). The experts can also be part of the members if possible (Benítez *et al.*, 2020; King *et al.*, 2023; Tran *et al.*, 2018; Vetter, 2020). The robust and sustained engagement among participants from various organizations and hierarchical levels within CoPs fosters the establishment of trust, which is essential for facilitating collective action and the implementation of development plans for governmental initiatives (Bonatti *et al.*, 2022). Therefore, at some point, collaboration with government or policy makers is encouraged in CoP as they become the authorities to make decision, enable actual action and conduct innovation at regional level for systemic change (Fulgenzi *et al.*, 2020; King *et al.*, 2023; Maiello, 2014; Mehring *et al.*, 2018; Nykvist, 2014; Orderud and Winsvold, 2012; Pahl-Wostl, 2009). Within the context of the community, the CoP incorporated leaders with various responsibilities, empowering them to act as agents of change essential for the collective advancement of the community (Morgan, 2011; Nykvist, 2014; Raymond and Robinson, 2013; Reed *et al.*, 2014; Tran *et al.*, 2018; Wulandhari *et al.*, 2021). Thus, learning activities in CoP have answered the needs for learning-based intervention of waste management so that it boosts public participation in a sustainable way.

Outcome from learning activities of cop

The output of learning activities is identified from previous studies and presented in Table 5.

As demonstrated in Table 5, Communities of Practice (CoP) play a significant role in promoting learning at multiple levels, encompassing individual collective (social), and systemic—contributing to a transformative shift in paradigms (King *et al.*, 2023). For single loop level, the study from Bonatti *et al.* (2022) found empirical evidence that 52 percent (%) relevance strength of CoP to knowledge diversity improvement has been achieved through CoP at community level. Similarly, King *et al.* (2023) found knowledge massive and skill expansion of NGOs and local government who have involved in CoP for biodiversity management improvement. Table 5 illustrates that double loop learning is more prominent at the individual and social levels, in contrast to single loop learning, which is primarily concerned with the improvement of technical competencies. The concept of double loop learning, which engenders changes at both the individual and social levels, is initiated through critical reflection on the specific domain. This reflection prompts a transformation in mindset and a reassessment of underlying values. At the next step, individual learning results intention to practice, changed behavior and value creation toward waste management activities. At social or collective level, the impact of double loop learning was the development of shared norms, social responsibility, unlearn past knowledge and habits and trust development among members. Empirical research has indicated that CoP yield significant impacts, particularly as manifestations of double loop learning. For instance, Sunarti *et al.* (2023) found CoP significantly improved members' awareness, personal and social responsibility and perceived value toward waste management activities from individuals joined the CoP, with impact up to moderate level (R^2 = 32%) when members involved both practice and dialogue-

Table 5: Outcome of learning activities in CoP from previous studies

No.	Learning output	Level of Learning	Type of Learning	Sources
1	Involve actively in the learning activities	Individual	Single loop learning	Didham *et al.*, 2017; Morgan, 2011; Noguera-Méndez *et al.*, 2016; Wulandhari *et al.*, 2021
2	Technical knowledge for practice	Individual	Single loop learning	Bonatti *et al.*, 2022; Bradbury and Middlemiss, 2015; Dolinska, 2016; King *et al.*, 2023; Maiello, 2014; Morgan, 2011; Nykvist, 2014; Odhiambo *et al.*, 2021; Sunarti *et al.*, 2023; Triste *et al.*, 2018
3	Awareness of consequence of their actions toward environment	Individual and social	Double loop learning	King *et al.*, 2023; Maiello, 2014; Mehring *et al.*, 2018; Noguera-Méndez *et al.*, 2016; Nykvist, 2014; Sunarti *et al.*, 2023; Wulandhari *et al.*, 2021
4	Changing attitude	Individual and social	Double loop learning	Triste *et al.*, 2018
5	Personal and social responsibility	Individual and social	Double loop learning	Mehring *et al.*, 2018; Nykvist, 2014; Sunarti *et al.*, 2023
6	Value creation toward the community domain	Individual and social	Double loop learning	Noguera-Méndez *et al.*, 2016; Nykvist, 2014; Sunarti *et al.*, 2023; Triste *et al.*, 2018
7	Intention to practice	Individual and social	Double loop learning	Dolinska, 2016; Mehring *et al.*, 2018; Noguera-Méndez *et al.*, 2016; Sunarti *et al.*, 2023
8	Changed behavior	Individual and social	Double loop learning	Bonatti *et al.*, 2022; Kim, 2017; Noguera-Méndez *et al.*, 2016; Sunarti *et al.*, 2023
9	More innovative; better performance	Social	Triple loop learning	Didham *et al.*, 2017; Dolinska, 2016; King *et al.*, 2023; Odhiambo *et al.*, 2021
10	Unlearn past knowledge and habits	Individual and social	Double loop learning	Vetter, 2020; Wulandhari *et al.*, 2021
11	Collaboration among members and outside the community	Social	Triple loop learning	Bonatti *et al.*, 2022; Didham *et al.*, 2017; Johnson and Wilson, 2000; King *et al.*, 2023; Mehring *et al.*, 2018; Morgan, 2011; Odhiambo *et al.*, 2021; Reed *et al.*, 2014
12	Shared norms among members (norms about sharing knowledge and community domain)	Individual and social	Double loop learning	Bradbury and Middlemiss, 2015; Didham *et al.*, 2017; Dolinska, 2016; Johnson and Wilson, 2000; Sunarti *et al.*, 2023
13	Developing new norms toward domain	Social	Triple loop learning	Bonatti *et al.*, 2022; Dolinska, 2016; Johnson and Wilson, 2000; King *et al.*, 2023; Maiello, 2014
14	Change or reframing value	Individual	Double loop learning	Bonatti *et al.*, 2022; Kim, 2017; King *et al.*, 2023; Triste *et al.*, 2018
15	Developing trust among members	Individual and social	Double loop learning	Bonatti *et al.*, 2022; Meessen *et al.*, 2011
16	Develop understanding (recognizing complexity of the problems)	Individual and social	Double loop learning	Bonatti *et al.*, 2022; Johnson and Wilson, 2000; King *et al.*, 2023; Meessen *et al.*, 2011; Mehring *et al.*, 2018
17	Critical reflection toward domain that cause mindset shifting	Individual and social	Double loop learning	Bonatti *et al.*, 2022; Didham *et al.*, 2017; Johnson and Wilson, 2000; King *et al.*, 2023; Triste *et al.*, 2018
18	Community Behavior transformation	Individual and social	Double loop learning and triple loop learning	Bonatti *et al.*, 2022
19	To make decision about certain intervention	System	Triple loop learning	Odhiambo *et al.*, 2021
20	Develop adaptive regulatory framework	System	Triple loop learning	Odhiambo *et al.*, 2021
21	Develop innovation to give solutions for the domain	System	Triple loop learning	Benítez *et al.*, 2020; Didham *et al.*, 2017; Noguera-Méndez *et al.*, 2016; Odhiambo *et al.*, 2021;

based activities. The effect increased when it was combined with facilities to accommodate practical learning (R^2 = 42%). Other study from Kim (2017) found that CoP involvement have changed community psychological factors and behavior significantly such as on environmental awareness (almost 90%), daily habits of food shopping (>80%), dietary (68.09%) and food waste management behavior (>70%), as a result of critical reflection, performing double loop learning. The empirical evidence indicated that over 50% of participants exhibited behavioral changes in three specific food consumption practices, with the most significant improvement observed in the group that had been engaged in the Community of Practice (CoP) for the extended period. It confirmed the requirement of durable intervention as implied by some studies on waste management context (Knickmeyer, 2020; Loan *et al*., 2017; Mehring *et al*., 2018; Oduro-Kwarteng *et al.,* 2016; Xu *et al*., 2018; Yeh *et al*., 2016). To achieve a more substantial impact, triple loop learning enabled the transformation of community behaviors, the adaptation of regulations, the emergence of various breakthrough innovations, and the establishment of new societal norms. The empirical evidence that showed the CoP outcome of triple loop learning is presented by some studies (Benítez *et al.*, 2020; Didham *et al.*, 2017; Noguera-Méndez *et al.*, 2016). Over the last two years, the efforts of PIAL, a CoP centered on local sustainable farming, have culminated in the emergence and adoption of new innovations within this domain (Benítez *et al.*, 2020; Noguera-Méndez *et al.*, 2016). Second, adapted regulatory frameworks and adapted standard SOP have been developed from LabCoP activity which concerns about hazardous waste management from HIV (Odhiambo *et al.*, 2021).

CoP design and multi loop learning model on waste management

After elaborating the previous findings from studies related to waste management and CoP implementation at various domains, including learning activities and learning outcome, it can be concluded that CoP implementation has been proven to enable transformation of various domain related to environmental management, including waste management. The transition from an individual perspective to a systemic framework arises from the results and outputs generated through multi-loop learning and collective endeavors. Thus, the proposed model of CoP and multi loop learning model, implementable for waste management domain at local and regional level are presented in Figs. 4 and 5. respectively.

The design of the CoP, as depicted in Fig. 4, is intended to bolster public involvement in waste management, promoting cooperative efforts that span from individual participants to community organizations and regional stakeholders. It consists of several CoPs at various level including local community level, across level at local and regional and within government organizations at local and regional level. Within local communities, a CoP can function as an informal venue for individuals to share insights and engage in discussions regarding waste management and related initiatives, thereby promoting active participation and interaction among community members. Such CoP was found in CoP from the study conducted by Tran *et al.* (2018); Ghazali *et al.* (2021); Sunarti *et al.* (2023) that allow individuals as the members of a civil society who have shared interest in recycling certain types of waste to learn together intensively within a CoP. The establishment of a CoP involving multiple stakeholders from various sectors at the community level is essential for fostering collaboration. This approach facilitates the exchange of knowledge, sharing of time and resources, and promotes collective action within local boundaries, as evidenced by several studies (Bonatti *et al.*, 2022; Goven *et al.*, 2012; Kim, 2017; Maiello, 2014). Cross sectoral CoPs are also required at national boundaries to become a bridge for resource and time sharing between local government agencies and CoP at community and regional level. Within government agencies—whether at the local, regional, or national level—the formation of CoP plays a critical role in enhancing coordination and collaboration among governmental bodies. Such cooperation is imperative for effective decision-making concerning waste management strategies and innovations, as well as for the adaptation of local and national regulatory frameworks to promote these advancements. Such CoP design was also found in several studies with various domains such as Johnson and Wilson (2000); Measham (2009); Beynen and Fleury (2010); Binot *et al.* (2015); Montero (2016) Didham *et al.* (2017); Granadino (2017). Consequently, multi-loop learning can be effective at the individual and

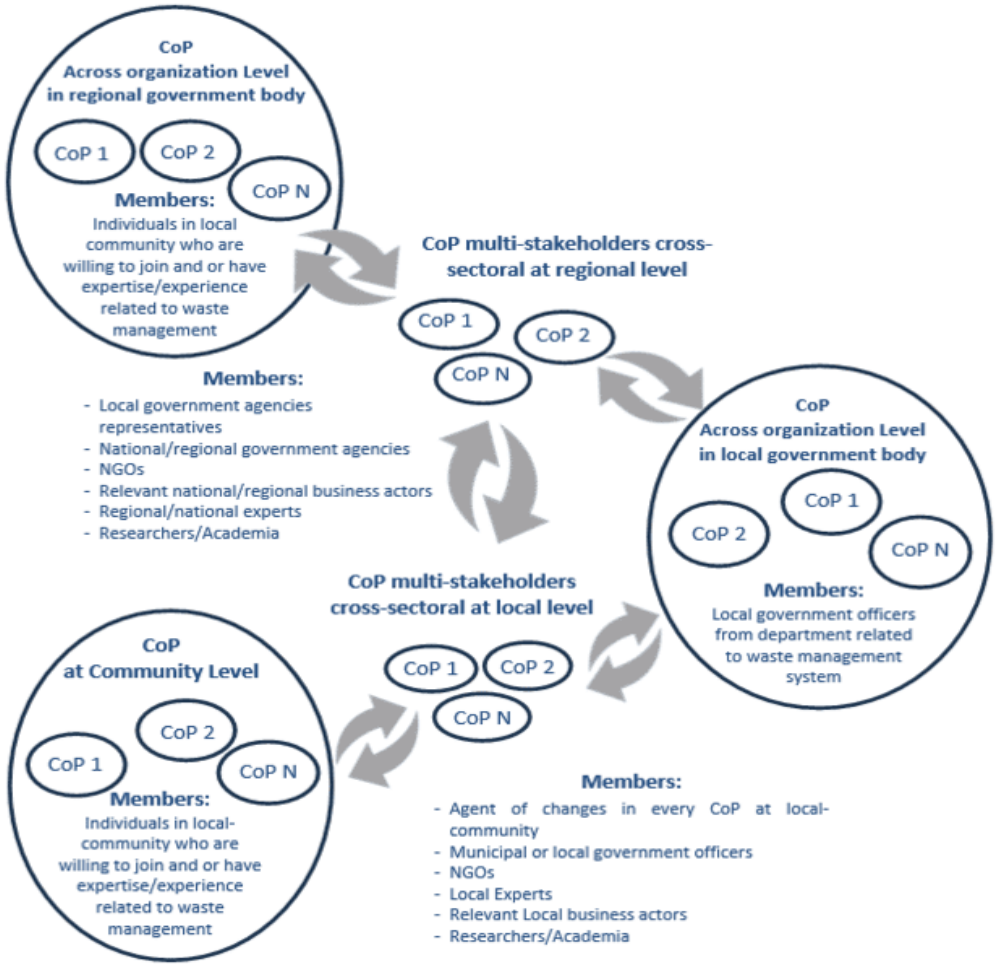


Fig. 4: CoP design for waste management system at local and regional level

community levels, as well as at the systemic level, facilitating significant and collective transformations in the waste management system necessary for a paradigm shift in waste management practices. In term of multi-loop learning, by comparing the basic model of multi loop learning theory presented by Hargrove (2002) and Pahl-Wostl (2009), and adapted model presented by Noguera-Méndez *et al.* (2016), combined with the findings from this literature review study, it was proposed the learning process model that accommodates multiple loop learning occur in CoPs in waste management system in developing countries, as presented in Fig. 5. The proposed model described every learning cycle and its outcome which occur within CoPs at every level. Learning loop processes can emerge from a range of collaborative endeavors, including direct interactions, informal meetings, collective practices, joint projects, and site visits, which should be regularly organized for all members over a sustained duration.

For model implementation, it is suggested to be initiated by government party as they have authority to conduct waste management system, either at local or regional level. Nevertheless, non-public stakeholders retain the ability to initiate the program independently and subsequently present it to the relevant authority in order to secure comprehensive support. This is vital as the power of the authority can enforce other non-public parties to join and involve. Due to the significant organizational efforts needed

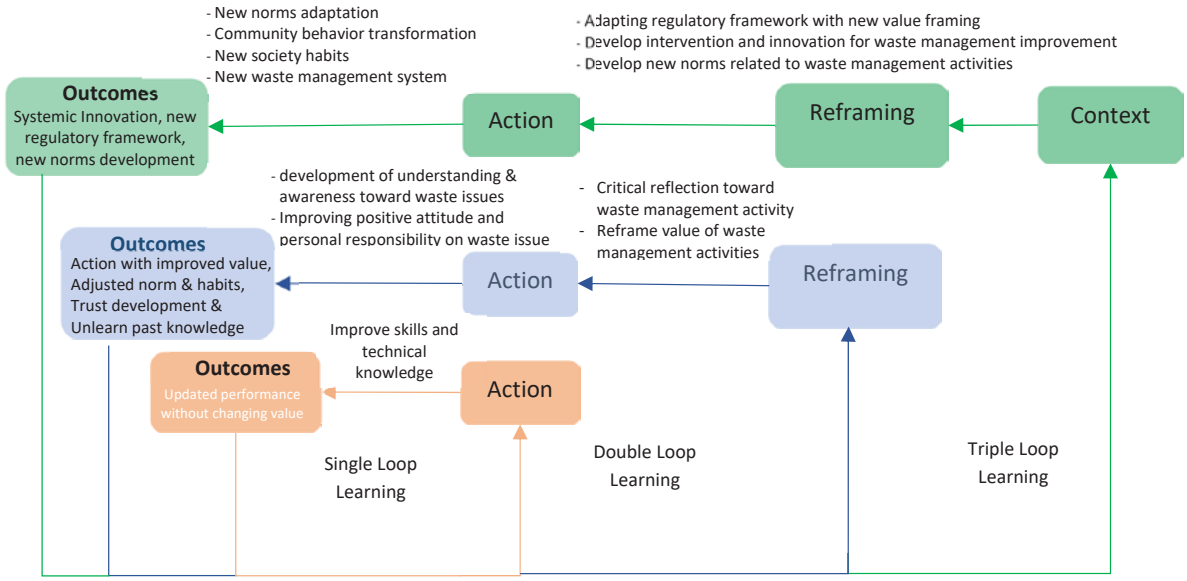


Fig. 5: Proposed multi-loop learning model on waste management system at developing country

across multiple sectors and levels, various potential challenges have surfaced, presenting barriers to the advancement of the CoP. First, egocentric tendency among parties can hinder collaborative intention across organizations. Such egocentric issue is inevitable, yet it can be decreased by starting the group in a small circle involving individuals from the expected organizations that already have interest to the waste issue domain. Second, willingness of the organizations to commit to join the CoP is also crucial. The CoP is fundamentally initiated through voluntary engagement, thereby encompassing only those individuals or groups who possess a common interest and aligned objectives within a specific domain (Wenger *et al.*, 2002; Wenger, 2010). The implementation has evolved become both voluntary or obligatory considering its vital goals. Thus, the implementation can be adjusted to the recent local condition and stakeholder's characteristics, whether it is more suitable to be voluntary or obligatory. Third, the requirement of time and resource sharing to facilitate joint activities, either communication-based activities (gathering, workshops, informal meetings, etc) or experiential-based activities (project collaboration, joint practice, etc) need commitment among the parties which can be burden for some individuals or organizations. Consequently, it is essential for dedicated members to reach a consensus in order to guarantee that the regular agenda is executed on schedule.

RECOMMENDATION

Social learning that facilitates multi-loop learning is required when it comes to transform waste management system to new paradigm where public active participation is expected to be sustainable. Paradigm shift from a government-dominated waste management framework to one that emphasizes collaboration requires extensive changes not only at the individual, community, and organizational levels across various sectors but also at the systemic level, in order to realize successful outcomes. Without involvement of all required parties, waste management tend to be less efficient if not face failure. As depicted in Fig. 4, the CoP model can act as a catalyst for collaboration among a range of entities, as it supports multi-loop learning for all parties involved. As implied in Fig. 5, multi loop learning performed in CoP provides gradual and continuous learning from the cognitive, affective, up to action at all level through intensive interactions and joint activities. The government need to facilitate this social learning system by developing CoPs at various level to conduct multiple joint activities related to

waste management. However, some obstacles can be challenges to start the CoP. Egocentric tendency, willingness to commit and requirement of time and resource to facilitate joint activities are some challenges that need to be taken into consideration. To implement effective solutions, it is essential to establish CoPs at various levels by motivating relevant stakeholders to participate voluntarily. This initiative can be spearheaded by local government entities, which hold the authority over waste management systems, or by other committed organizations dedicated to addressing waste-related challenges. As time progresses, the CoP has the potential to grow and extend naturally, thereby attracting a wider array of relevant participants. Further development can expand the CoPs coverage by instituting compulsory participation for the anticipated parties that have yet to enroll in the program.

CONCLUSION

Public participation in waste management system is vital through collaborative system among various stakeholders. The absence of collaboration will burden the operational cost and reduce the effectiveness of the waste management process especially for developing countries which typically have limited budget for waste management. The typical system implemented in waste management in many developing countries commonly highly rely on government to handle the waste from scratch. Increasing public participation through social learning seemed to be promising as social learning can facilitate collaboration across sectors and across community and organization from various levels while also encourage multi loop learning among stakeholders involved that support individual to systemic transformation. This study provided argumentation based on previous study review related to the potency of CoP as social learning platform to enable learning-based intervention strategies to boost sustainable participation of public community in waste management. This study confirmed the requirement of social learning implementation to enable public participation in waste management system sustainably. It is because social learning enables multi loop learning intended to transform individual and collective behavioral change to support waste management transformation. The collaborative action from multi stakeholders across sectors and organizations is indeed vital for the effectiveness of waste management improvement. The multi-loop learning encourages massive change from individual to system so that innovation and new norm development can be well supported. The single loop learning performed technical development at individual or collective level, such as the technique of treating waste without questioning the value of the action. The double loop learning empowered the learning effect by facilitating critical reflection that improved individual and social understanding as well as awareness toward waste issues, develop personal and social responsibilities which in turn questioning the current norms related to the habits on waste management. The third loop learning facilitates systemic real action as the follow up of the double loop learning such as regulation improvement, innovation and new norm development that adopt the new value. Finally, it is proposed a model of CoP platform strategy that defined the stakeholders and pictured the inter-relationship among members in the CoP at community, organization and municipal level, across level and across sectors, which is implementable to municipal government in developing countries. Possible challenges may arise as it involved diverse parties to involve. Starting the CoP initiated by local government or other possible party who have high commitment to waste issues and involve other parties who have similar interest can be a good start to reduce the barrier. This finding is crucial for government agencies at local and regional area in many developing countries to get insight how to develop CoP and determine the expected output and outcome of the CoP for better waste management transformation. Main contribution and the novelty of the study is the proposed model that describes comprehensively the inter-relationship among parties across level and sectors and the multi loop learning model which have not been given by any previous studies. Further studies are required to testify the model design and measure its effectiveness in nurturing learning outcomes for every loop of learning using action research approach.

AUTHOR CONTRIBUTIONS

Sunarti conceptualized the research design, conducted literature review, data curation and data analysis, wrote the original draft. M. Nuryana conceptualized the research design and data curation,

wrote the original draft, supervised the review process, and validated the findings. W. Wiryanto conducted the literature searching, performed formal analysis, writing the review, and validated the findings. Buyamin conducted the literature searching, performed formal analysis, writing the review, and validated the findings. A. Aswin wrote the original draft, performed the literature review and manuscript editing. C. Permatasari conducted literature review, performed manuscript editing and project administration. J.H. Tjakraatmadja conceptualized the research design and validated the findings.

ACKNOWLEDGEMENT

This study has not received any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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

©2024 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
BRP	Bucket revolution project
CBRA	Canadian Biosphere Reserve Association
CDI	Catchment demonstration initiative
CDS	Cidade do saber
CoP	Community of practice
CoP N	Community of practice N^{th} number
EAG	Environmental action group
ESD	Education for sustainable development
FGD	Focus group discussion
HIV	Human Immunodeficiency Virus
KIP	Karst information portal
KBS	*Kawasan Bebas Sampah*/Zero Waste Area
LTCCP	Long Term Council Community Plans
LabCoP	Laboratory Community of Practice
NGO	Non-government organization
NVIVO 12	A qualitative data analysis software provided by QSR International
NFM	Natural Flood Management
NGOs	Non-governmental organization
PBF	Performance-based financing
PIAL	Participatory Seed Diffusion Program
PlanCC Project	Planning for Climate Change
PFLA	Pasture-Fed Livestock Association
SSA Countries	Sub-Saharan Africa Countries
SPR	*Sekolah Peternakan Rakyat*/ Farmer Breeder School
UK	United Kingdom
USA	United States of America
VMD	Vietnamese metkong delta
WM	Waste management

REFERENCES

Abbasi, S.A., (2018). The myth and the reality of energy recovery from municipal solid waste. Energy Sustainability Soc., 8(36): 1–15 **(15 pages).**

Anuardo, R.G.; Espuny, M.; Costa, A.C.F.; Oliveira, O.J., (2022). Toward a cleaner and more sustainable world: A framework to develop and improve waste management through organizations, governments and academia. Heliyon. 8(4): 1–15 **(15 pages).**

Ain, K. Q.; Nasri, M. A.; Alamsyah, M. N.; Pratama, M. D. R.; Kurniawan, T. (2021). Collaborative governance in managing plastic waste in Bali. IOP Conference Series: Earth Environ. Sci, 905(1): 1 – 12 **(12 pages).**

Arantes, V.; Zou, C.; Che, Y. (2020). Coping with waste: A government-NGO collaborative governance approach in Shanghai. J. Environ. Manage., 259: 1 – 8 **(8 pages)**.

Atta, A.B.; Imoro, A.Z.; Agyemang, R.O.; Acheampong, N.A., (2023). The assessment of personal protective equipment waste management in a developing neighbourhood: Examples of Tamale metropolis. Cleaner Waste Syst., 6: 1–11 **(11 pages).**

Banerjee, S.; Sarkhel, P. (2019). Municipal solid waste management, household and local government participation: a cross country analysis. J. Environ. Plann. Manage., 63(2), 210–235 **(27 pages)**.

Beattie, T.; Belmans, N.; Carbol, P.; Cowley, M.; Faltejsek, J.; Grambow, B.; Holt, E.; Salat, E.; Tatomir, A.; Théodon, L.; Winsley, R.; Zuidema, P., (2022). Overview of knowledge management in EURAD. EPJ Nuclear Sci. Technol., 8: 1-10 **(10 pages).**

Benítez, B.; Nelson, E.; Romero Sarduy, M.I.; Ortíz Pérez, R.; Crespo Morales, A.; Casanova Rodríguez, C.; Campos Gómez, M.; Méndez Bordón, A.; Martínez Massip, A.; Hernández Beltran, Y.; and Daniels, J. (2020). Empowering women and building sustainable food systems: A case study of Cuba's local agricultural innovation project. Front. Sustainable Food Syst., 4: 1–17 **(17 pages).**

Beynen, K. Van.; Fleury, E.S., (2010). Learning and engaging the information values of a karst community of practice. J. Acad. Librarianship. 36(1): 79–85 **(7 pages).**

Binot, A.; Duboz, R.; Promburom, P.; Phimpraphai, W.; Cappelle, J.; Lajaunie, C.; Luce, F.; Pinyopummintr, T.; Figuié, M.; Louis, F., (2015). A framework to promote collective action within the one health community of practice: Using participatory modelling to enable interdisciplinary, cross-sectoral and multi-level integration. ONEHLT. 1: 44–48 **(5 pages).**

Bonatti, M.; Erismann, C.; Askhabalieva, A.; Borba, J.; Pope, K.; Reynaldo, R.; Eufemia, L.; Turetta, A. P.; Sieber, S., (2022). Social learning as an underlying mechanism for sustainability in neglected communities: The Brazilian case of the bucket revolution project. Environ. Dev. Sustainability. 1: 1–19 **(19 pages).**

Bradbury, S.; Middlemiss, L., (2015). The role of learning in sustainable communities of practice. Local Environ., 20(7): 796–810 **(15 pages).**

Chen, L.; Gao, M., (2020). A new learning interaction rule for municipal household waste classification behavior based on multi-agent-based simulation. J. Cleaner Prod., 271: 1–13 **(13 pages).**

Chikowore, N., (2020). Factors influencing household waste management practices in Zimbabwe. J. Mater. Cycles Waste Manage., 23: 386–393 **(8 pages).**

Chow, C.-F.; So, W.-M.W.; Cheung, T.-Y.; Yeung, S.-K.D., (2017). Plastic waste problem and education for plastic waste management. In S. C. Kong, T. L. Wong, M. Yang, C. F. Chow, and K. H. Tse (Eds.), Emerging practices in scholarship of learning and teaching in a digital era. Springer Nature. 125–140 **(16 pages).**

Cishahayo, L.; Yang, Q.; Zhu, Y.; Wang, F., (2022). Learning behavior, environmental awareness, and agricultural waste management of banana farmers in China. Soc. Behav. Pers., 50(5): 1–11 **(11 pages).**

Davis, J.; Mengersen, K.; Bennett, S.; Mazerolle, L., (2014). Viewing systematic reviews and meta-analysis in social research through different lenses. SpringerPlus. 3(511): 1–9 **(9 pages).**

Ddiba, D.; Andersson, K.; Koop, S.H.A.; Ekener, E.; Finnveden, G.; Dickin, S., (2020). Governing the circular economy: assessing the capacity to implement resource-oriented sanitation and waste management systems in low- and middle-income countries. Earth Syst. Governance. 4: 1–11 **(11 pages).**

Didham, R.J.; Ofei-Manu, P.; Nagareo, M., (2017). Social learning as a key factor in sustainability transitions: The case of Okayama city. Int. Rev. Edu., 63(6): 829–846 **(18 pages).**

Dolinska, A., (2016). Farmers as agents in innovation systems. Empowering farmers for innovation through communities of practice. Agric. Syst., 142: 122–130 **(9 pages).**

Einhäupl, P.; Krook, J.; Svensson, N.; Van Acker, K.; Van Passel, S., (2019). Eliciting stakeholder needs – an anticipatory approach assessing enhanced landfill mining. Waste Manage., 98: 113–125 **(13 pages).**

Elayan, M.; Ibrawish, E., (2017). Factors influencing the implementation of recycling: Evidence from ayla aviation academy in Jordan. Int. J. Economic Perspectives Econ. Perspect., 11(1): 354–377 **(24 pages).**

Essen, E. von; van Heijgen, E.; Gieser, T., (2019). Hunting communities of practice: factors behind the social differentiation of hunters in modernity. J. Rural Stud., 68: 13–21 **(9 pages).**

Fredrick, M.; Oonyu, J.C.; Sentongo, J., (2018). Influence of education on the solid waste management practices of communities in Kampala city. 5(1): 261–274 **(14 pages).**

Fulgenzi, A.; Brouwer, S.; Baker, K.; Frijns, J., (2020). Communities of practice at the center of circular water solutions. Wiley Interdiscip. Rev.: Water. 7(4): 1–15 **(15 pages).**

Gars, J.; Ward, P.S., (2019). Can differences in individual learning explain patterns of technology adoption? Evidence on heterogeneous learning patterns and hybrid rice adoption in Bihar, India. World Dev., 115: 178–189 **(12 pages).**

Ghazali, A.; Tjakraatmadja, J.H.; Sunarti; Pratiwi, E.Y.D.Y.D., (2021). Resident-based learning model for sustainable resident participation in municipal solid waste management program. Global J. Environ. Sci. Manage., 7(4): 599–624 **(26 pages).**

Goven, J.; Langer, E.R.; Baker, V.; Ataria, J.; Leckie, A., (2012). Community engagement in the management of biosolids: Lessons from four New Zealand studies. J. Environ. Manage., 103: 154–164 **(11 pages).**

Granadino., (2017). Institutional and political factors in creating a community of practice on mitigation: The case of plancc, Peru. Dev., (2016): 342–349 **(8 pages).**

Gyimah, P.; Mariwah, S.; Antwi, K.B.; Ansah-Mensah, K., (2019). Households' solid waste separation practices in the cape coast metropolitan area, Ghana. Geo-Journal. 4: 1–17 **(17 pages).**

Hargrove, R., (2002). Masterful coaching. Jossey-Bass, San Francisco **(432 pages)**.

Idamah, A.P., (2015). Influence of broadcast media enlightenment campaigns on solid waste management in south-south of Nigeria. New Media Mass Commun., 39: 10–62 **(54 pages).**

Izdebska, O.; Knieling, J. (2020). Citizen Involvement in Waste Management and Circular Economy in Cities: Key Elements. Europe. Spat. Res. and Pol., 27(2), 115–129 **(15 pages).**

Jiang, P.; Fan, Y. Van; Klemeš, J.J., (2021). Data analytics of social media publicity to enhance household waste management. Resour. Conserv. Recycl., 164: 1–12 **(12 pages).**

Johnson, H.; Wilson, G., (2000). Biting the bullet: Civil society, social learning and the transformation of local governance. DPP Work. Pap. - Open Univ., 28(11): 1891–1906 **(6 pages).**

Jordan, J.M.; Hoggarth, J.A.; Awe, J.J., (2020). Pottery, practice, and place: A communities of practice approach to commoner interaction in the late to terminal classic Belize river valley. J. Anthropol. Archaeol., 58: 1–20 **(20 pages).**

Keen, M.; Mahanty, S., (2006). Learning in sustainable natural resource management: Challenges and opportunities in the pacific. Soc. Nat. Resour., 19(6): 497–513 **(17 pages).**

Kim, J.E., (2017). Fostering behavior change to encourage low-carbon food consumption through community gardens. Int. J. Urban Sci.,

21(3): 364–384 **(19 pages).**
King, P.; Martin-Ortega, J.; Armstrong, J.; Ferré, M.; Bark, R.H., (2023). Mainstreaming nature-based solutions: What role do communities of practice play in delivering a paradigm shift? Environ. Sci. Policy. 144: 53□63 **(11 pages).**
Knickmeyer, D., (2020). Social factors influencing household waste separation: A literature review on good practices to improve the recycling performance of urban areas. J. Cleaner Prod., 245: 1–41 **(41 pages).**
Kristjanson, P.; Harvey, B.; Van Epp, M.; Thornton, P.K., (2014). Social learning and sustainable development. Nat. Clim. Change. 4(1): 5–7 **(2 pages).**
Lee, C.K.M.; Ng, K.K.H.; Kwong, C.K.; Tay, S.T., (2019). A system dynamics model for evaluating food waste management in Hong Kong, China. J. Mater. Cycles Waste Manage., 21: 433–456 **(26 pages).**
Liao, C.; Zhao, D.; Zhang, S.; Chen, L., (2018). Determinants and the moderating effect of perceived policy effectiveness on residents' separation intention for rural household solid waste. Int. J. Environ. Res. Public Health. 15(726): 1–17 **(17 pages).**
Limon, M.R.; Vallente, J.P.C.; Corales, N.C.T., (2020). Solid waste management beliefs and practices in rural households towards sustainable development and pro-environmental citizenship. Glob. J. Environ. Sci. Manage., 6(4): 441–456 **(16 pages).**
Lissah, S.Y.; Ayanore, M.A.; Krugu, J.K.; Aberese-Ako, M.; Ruiter, R.A.C., (2021). Managing urban solid waste in Ghana: Perspectives and experiences of municipal waste company managers and supervisors in an urban municipality. PLoS ONE. 16: 1–19 **(19 pages).**
Liu, X.; Wang, Z.; Li, W.; Li, G.; Zhang, Y., (2019). Mechanisms of public education influencing waste classification willingness of urban residents. Resour. Conserv. Recycl., 149: 381–390 **(10 pages).**
Loan, L.T.T.; Nomura, H.; Takahashi, Y.; Yabe, M., (2017). Psychological driving forces behind households' behaviors toward municipal organic waste separation at source in Vietnam: A structural equation modeling approach. J. Mater. Cycles Waste Manage., 19: 1052–1060 **(9 pages).**
Ma, J.; Hipel, K.W.; Hanson, M.L., (2018). An evaluation of the social dimensions in public participation in rural domestic waste source-separated collection in Guilin, China. Environ. Monit. Assess., 190(35): 1–14 **(14 pages).**
Maiello, A., (2014). The organizational view of public participation: A narrative analysis. Syst. Pract. Action Res., 27(5): 499–522 **(24 pages).**
Mamady, K., (2016). Factors influencing attitude, safety behavior, and knowledge regarding household waste management in Guinea: A cross-sectional study. J. Environ. Public Health. 2016(9305768): 1–9 **(9 pages).**
Maryati, S.; Arifiani, N.F.; Humaira, A.N.S.; Putri, H.T., (2018). Factors influencing household participation in solid waste management (case study: waste bank Malang). IOP Conference Series: Earth Environ. Sci, 124: 1–5 **(5 pages)**.
Measham, T.G., (2009). Social learning through evaluation: A case study of overcoming constraints for management of dryland salinity. Environ. Manage., 43(6): 1096–1107 **(12 pages).**
Meessen, B.; Kouanda, S.; Musango, L.; Richard, F., (2011). Communities of practice: The missing link for knowledge management on implementation issues in low-income countries? Trop. Med. Int. Health. 16(8): 1007–1014 **(8 pages).**
Mehring, P.; Geoghegan, H.; Cloke, H.L.; Clark, J.M., (2018). What is going wrong with community engagement? How flood communities and flood authorities construct engagement and partnership working. Environ. Sci. Policy. 89: 109–115 **(17 pages).**
Merson, J.; Attwater, R.; Ampt, P.; Wildman, H.; Chapple, R., (2011). The challenges to urban agriculture in the Sydney basin and lower blue mountains region of Australia. Urban Agric.: Divers. Act. Benefits City Soc., 5903: 72–85 **(14 pages).**
Montero, C.G., (2016). Communities of practice at the cidade do saber plural citizenship and social inclusion in Brazil. Anthropol. Act. 2(2): 19–26 **(8 pages).**
Morgan, S.L., (2011). Social learning among organic farmers and the application of the communities of practice framework. J. Agric. Educ. Ext., 17(1): 99–112 **(14 pages).**
Mukama, T.; Ndejjo, R.; Musoke, D.; Musinguzi, G.; Halage, A.A.; Carpenter, D.O.; Ssempebwa, J.C., (2016). Practices, concerns, and willingness to participate in solid waste management in two urban slums in Central Uganda. J. Environ. Public Health. 2016: 1–7 **(7 pages).**
Navykarn, K.; Muneenam, U., (2015). Waste management education for sustainable islands. Appl. Mech. Mater., 804: 271–274 **(4 pages).**
Nepal, M.; Karki Nepal, A.; Khadayat, M.S.; Rai, R.K.; Shyamsundar, P.; Somanathan, E., (2023). Low-cost strategies to improve municipal solid waste management in developing countries: experimental evidence from Nepal. Environ. Resour. Econ., 84(3): 729–752 **(24 pages).**
Noguera-Méndez, P.; Molera, L.; Semitiel-García, M., (2016). The role of social learning in fostering farmers' pro-environmental values and intentions. J. Rural Stud., 46(2016): 81–92 **(12 pages).**
Nykvist, B., (2014). Does social learning lead to better natural resource management? A case study of the modern farming community of practice in Sweden. Soc. Nat. Resour., 27(4): 436–450 **(15 pages).**
Odhiambo, C.O.; Mataka, A.; Kassa, G.; Ondoa, P., (2021). Managing laboratory waste from HIV-related molecular testing: Lessons learned from African countries. J. Hazard. Mater. Lett., 2: 1–8 **(8 pages).**
Oduro-Kwarteng, S.; Anarfi, K.P.; Essandoh, H.M.K., (2016). Source separation and recycling potential of municipal solid waste in Ghana. Manage. Environ. Qual.: Int. J., 27(2): 210–226 **(16 pages).**
Orderud, G.I.; Winsvold, M., (2012). The role of learning and knowledge in adapting to climate change: A case study of Norwegian municipalities. Int. J. Environ. Stud., 69(6): 946–961 **(16 pages).**
Padilla, A.J.; Trujillo, J.C., (2017). Waste disposal and households-heterogeneity. Identifying factors shaping attitudes towards source-separated recycling in Bogotá, Colombia. Waste Manage., 74: 16-33 **(18 pages).**
Pahl-Wostl, C., (2009). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environ. Change, 19(3): 354–365 **(12 pages).**
Pei, Z., (2019). Roles of neighborhood ties, community attachment and local identity in residents' household waste recycling intention. J. Cleaner Prod., 241: 1–9 **(9 pages).**
Pierini, V.I.; Mazzeo, N.; Cazenave, M.; Semmartin, M., (2021). Waste generation and pro-environmental behaviors at household level: A citizen science study in Buenos Aires (Argentina). Resour. Conserv. Recycl., 170: 1–7 **(7 pages).**
Premakumara, D.G.J.; Abe, M.; Maeda, T., (2011). Reducing municipal waste through promoting integrated sustainable waste management (iswm) practices in Surabaya city, Indonesia. Ecosyst. Sustainable Dev., 144: 457–468 **(12 pages).**
Ramadan, B.S.; Alam, F.C.; Rahardyan, B., (2016). The influence of environmental campaign on public awareness in maintaining the cleanliness and waste reduction program: a case study of Bandung City. Sci. J. PPI-UKM, 3(1): 32–37 **(6 pages).**
Raymond, C.M.; Robinson, G.M., (2013). Factors affecting rural landholders' adaptation to climate change: Insights from formal institutions and communities of practice. Global Environ. Change. 23(1): 103–114 **(12 pages).**
Reed, M.G.; Godmaire, H.; Abernethy, P.; Guertin, M.A., (2014). Building

a community of practice for sustainability: Strengthening learning and collective action of Canadian biosphere reserves through a national partnership. J. Environ. Manage., 145: 230–239 **(10 pages).**

Sari, M.D.P.; Umanto., (2013). The Design of change in waste management policy: application of soft systems methodology. BIS. BIROKRASI: J. Ilmu Adm. Organ., 20(3): 153–162 **(10 pages).**

Sayara, T.; Hanoun, R.; Hamdan, Y., (2022). Survey on the factors and social perspectives to participate in home composting schemes in Palestine: Anabta case study. AIMS Environ. Sci., 9(3): 216–227 **(12 pages).**

Sekito, T.; Matsuyama, A.; Budi, T.; Yutaka, P., (2020). Factors influencing the period of participation in a waste bank system in Malang City, Indonesia. J. Mater. Cycles Waste Manage., 22: 1614–1619 **(6 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: 1–12 **(12 pages).**

Singer, J.; Kieu, K.T.; Pravitasari, A.E., (2019). Solid waste management in tourist destinations in developing nations: Case studies in Hoi An, Vietnam, and Puncak, Indonesia. In W. W. M. So, C. F. Chow, and J. C. K. Lee (Eds.). Environmental Sustainability and Education for Waste Management. 189–206 **(8 pages).**

Song, Q.; Wang, Z.; Li, J., (2016). Exploring residents' attitudes and willingness to pay for solid waste management in Macau. Environ. Sci. Pollut. Res., 23(16): 16456–16462 **(7 pages).**

Sun, Y. (2015). Facilitating generation of local knowledge using a collaborative initiator: A NIMBY case in Guangzhou, China. Habitat Int., 46, 130–137: **(8 pages).**

Sunarti, S.; Zebua, R.S.Y.; Tjakraatmadja, J.H.; Ghazali, A.; Rahardyan, B.; Koeswinarno, K.; Suradi, S.; Nurhayu, N.; Ansyah, R. H.A., (2023). Social learning activities to improve community engagement in waste management program. Global J. Environ. Sci. Manage., 9(3): 403–426 **(24 pages).**

Sunarti; Tjakraatmadja, J.H.; Ghazali, A.; Rahardyan, B., (2021). Increasing resident participation in waste management through intrinsic factors cultivation. Global J. Environ. Sci. Manage., 7(2): 287–316 **(30 pages).**

Tiew, K.G.; Ahmad Basri, N.E.; Watanabe, K.; Abushammala, M.F.M.; Bin Ibrahim, M.T., (2015). Assessment of the sustainability level of community waste recycling program in Malaysia. J. Mater. Cycles Waste Manage., 17(3): 598–605 **(8 pages).**

Tobin, S.; Zaman, A. (2022). Regional cooperation in waste management: Examining Australia's experience with inter-municipal cooperative partnerships. Sustainability. 14(3):1-46 **(46 pages)**.

Tran, T.A.; James, H.; Pittock, J., (2018). Social learning through rural communities of practice: Empirical evidence from farming households in the Vietnamese mekong delta. Lear. Cult. Soc. Interact., 16: 31–44 **(14 pages).**

Trihadiningrum, Y.; Laksono, I.J.; Dhokhikah, Y.; Moesriati, A.; Radita, D.R.; Sunaryo, S., (2017). Community activities in residential solid waste reduction in Tenggilis Mejoyo District, Surabaya City, Indonesia. J. Mater. Cycles Waste Manage., 19(1): 526–535 **(10 pages).**

Triste, L.; Debruyne, L.; Vandenabeele, J.; Marchand, F.; Lauwers, L., (2018). Communities of practice for knowledge co-creation on sustainable dairy farming: Features for value creation for farmers. Sustainability Sci., 13: 1427–1442 **(17 pages).**

Ulhasanah, N.; Goto, N., (2018). Assessment of citizens' environmental behavior toward municipal solid waste management for a better and appropriate system in Indonesia: A case study of Padang City. J. Mater. Cycles Waste Manage., 20(2): 1257–1272 **(16 pages).**

Vetter, T., (2020). Social (un-)learning and the legitimization of marginalized knowledge: How a new community of practice tries to 'kick the grain habit' in ruminant livestock farming. J. Rural Stud., 79: 11–23 **(13 pages).**

Vlachokostas, C., (2020). Closing the loop between energy production and waste management: A conceptual approach towards sustainable development. Sustainability. 12(15): 1–15 **(15 pages).**

Wang, F.; Cheng, Z.; Reisner, A.; Liu, Y., (2018). Compliance with household solid waste management in rural villages in developing countries. J. Cleaner Prod., 202: 293–298 **(6 pages).**

Wang, H.; Liu, X.; Wang, N.; Zhang, K.; Wang, F.; Zhang, S.; Wang, R.; Zheng, P.; Matsushita, M., (2020). Key factors influencing public awareness of household solid waste recycling in urban areas of China: A case study. Resour. Conserv. Recycl., 158: 1–9 **(9 pages).**

Wang, Z.; Huo, J., (2023). Do government intervention measures promote e-waste recycling in China? J. Environ. Manage., 342: 1–10 **(10 pages).**

Wenger, E., (2010). Communities of practice and social learning systems: The career of a concept. Social learning systems and communities of practice. 179–198 **(20 pages)**.

Wenger, E.; McDermott, R.A.; Snyder, W.M., (2002). Cultivating communities of practice: A guide to managing knowledge. Harvard Business Press, Boston **(284 pages).**

Wulandhari, N.B.I.; Mishra, N.; Dora, M.; Samuel, F.W., (2021). Understanding rural do-it-yourself science through social learning in communities of practice. Echnol. Forecast. Soc. Change. 163: 1–11 **(11 pages).**

Xu, L.; Ling, M.; Lu, Y.; Shen, M., (2017). Understanding household waste separation behavior: testing the roles of moral, past experience, and perceived policy effectiveness within the theory of planned behavior. Sustainability. 9(4): 1–27 **(27 pages).**

Xu, L.; Ling, M.; Wu, Y., (2018). Economic incentive and social influence to overcome household waste separation dilemma: A field intervention study. Waste Manage., 77: 522–531 **(10 pages).**

Yeh, L.-T.; Chang, D.-S.; Liu, W., (2016). The effect of organizational learning on the dynamic recycling performance of Taiwan's municipal solid waste (msw) system. Clean Technol. Environ. Policy. 18(5): 1535–1550 **(16 pages).**

Yuan, Y.; Nomura, H.; Takahashi, Y.; Yabe, M., (2016). Model of chinese household kitchen waste separation behavior: A case study in Beijing city. Sustainability. 8(10): 1–15 **(15 pages).**

Yukalang, N.; Clarke, B.; Ross, K., (2017). Barriers to effective municipal solid waste management in a rapidly urbanizing area in Thailand. Int. J. Environ. Res. Public Health. 14(1013): 1–23 **(23 pages).**

Zahra, K.; Majeed, K.; Mahmood, A.; Asad, M., (2012). Impact assessment of community participation in solid waste management projects in selected areas of Faisalabad City. J. Urban Plann. Dev., 138(4): 319–328 **(10 pages).**

Zamri, G.B.; Azizal, N.K.A.; Nakamura, S.; Okada, K.; Nordin, N.H.; Othman, N.; MD Akhir, F.N.; Sobian, A.; Kaida, N.; Hara, H., (2020). Delivery, impact and approach of household food waste reduction campaigns. J. Cleaner Prod., 246: 1–22 **(22 pages).**

Zhang, J.; Zhu, M., (2022). Collaborative governance of municipal solid waste in urban agglomerations: The case of Yangtze River Delta. Front. Environ. Sci., 10(October), 1–8 **(8 pages)**.

Zebua, R.S.Y.; Sunarti., (2021). The Implementation of character building to improve resident participation in waste management. IOP Conference Series: Earth Environ. Sci., 810(1): 1–6 **(6 pages).**

Zheng, J.; Ma, G.; Wei, J.; Wei, W.; He, Y.; Jiao, Y.; Han, X., (2020). Evolutionary process of household waste separation behavior based on social networks. Resour. Conserv. Recycl., 161: 1–14 **(14 pages).**

AUTHOR (S) BIOSKETCHES

Sunarti, Ph.D., Researcher, Research Center for Public Policy, National Research and Innovation Agency (BRIN), Jl. Gatot Subroto No. 10, Kuningan Bar., Kec. Mampang Prapatan, Kota Jakarta Selatan, DKI Jakarta, Indonesia.
- Email: *suna036@brin.go.id*
- ORCID: 0000-0002-6332-5190
- Web of Science ResearcherID: AAC-7113-2021
- Scopus Author ID: 57282085400
- Homepage: https://www.researchgate.net/profile/Sunarti-Sunarti

Nuryana, M., Ph.D., Researcher, Research Center for Public Policy, National Research and Innovation Agency (BRIN), Jl. Gatot Subroto No. 10, Kuningan Bar., Kec. Mampang Prapatan, Kota Jakarta Selatan, DKI Jakarta, Indonesia.
- Email: *muma001@brin.go.id*
- ORCID: 0000-0001-9997-4750
- Web of Science ResearcherID: NA
- Scopus Author ID: 57223229321
- Homepage: https://brin.go.id/ortkpekm/pusat-riset-kebijakan-publik/page/personil

Wiryanto, W., Ph.D., Researcher, Research Center for Public Policy, National Research and Innovation Agency (BRIN), Jl. Gatot Subroto No. 10, Kuningan Bar., Kec. Mampang Prapatan, Kota Jakarta Selatan, DKI Jakarta, Indonesia.
- Email: *wisb001@brin.go.id*
- ORCID: 0000-0003-3408-0021
- Web of Science ResearcherID: NA
- Scopus Author ID: 59304750100
- Homepage: https://brin.go.id/ortkpekm/pusat-riset-kebijakan-publik/page/personil

Buyamin, M.Si., Researcher, Research Center for Public Policy, National Research and Innovation Agency (BRIN), Jl. Gatot Subroto No. 10, Kuningan Bar., Kec. Mampang Prapatan, Kota Jakarta Selatan, DKI Jakarta, Indonesia.
- Email: *buya001@brin.go.id*
- ORCID: 0000-0002-1435-6978
- Web of Science ResearcherID: NA
- Scopus Author ID: 58655548800
- Homepage: https://brin.go.id/ortkpekm/pusat-riset-kebijakan-publik/page/personil

Aswin, A., M.AP., Researcher, Research Center for Public Policy, National Research and Innovation Agency (BRIN), Jl. Gatot Subroto No. 10, Kuningan Bar., Kec. Mampang Prapatan, Kota Jakarta Selatan, DKI Jakarta, Indonesia.
- Email: *azwa002@brin.go.id*
- ORCID: 0000-0003-1623-7312
- Web of Science ResearcherID: NA
- Scopus Author ID: 58991571500
- Homepage: https://brin.go.id/ortkpekm/pusat-riset-kebijakan-publik/page/personil

Permatasari, C., M.AP., Researcher, Researcher, Research Center for Public Policy National Research and Innovation Agency (BRIN), Jl. Gatot Subroto No. 10, Kuningan Bar., Kec. Mampang Prapatan, Kota Jakarta Selatan, DKI Jakarta, Indonesia.
- Email: *citr009@brin.go.id*
- ORCID: 0000-0002-3294-7675
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/ortkpekm/pusat-riset-kebijakan-publik/page/personil

Tjakraatmadja, J.H., Ph.D., Professor, School of Business and Management, Bandung Institute of Technology (ITB), Jl. Ganesa No.10, Lb. Siliwangi, Kota Bandung, Jawa Barat, Indonesia.
- Email: *jannhidajat@sbm-itb.ac.id*
- ORCID: 0000-0003-2940-2401
- Web of Science ResearcherID: HJB-0148-2022
- Scopus Author ID: 55437078200
- Homepage: https://www.sbm.itb.ac.id/member/jannhidajat/

HOW TO CITE THIS ARTICLE

Sunarti; Nuryana, M.; Wiryanto, W.; Aswin, A.; Buyamin; Permatasari, C., Tjakraatmadja, J.H., (2024). Intervention strategy for sustainable waste management systems in developing countries using community of practice. Global J. Environ. Sci. Manage., 10 (SI): 323-348.

DOI: 10.22034/gjesm.2024.10.SI.20

URL: https://www.gjesm.net/article_715545.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

Global
Journal of Environmental Science and Management

CONTENTS

Volume 10(SI), Special Issue, 2024

Optimal cropping patterns using linear programming and evaluation based on food-energy-water nexus	**(1 - 18)**
Dark septate endophytes symbiosis in Falcataria moluccana and its potency for forest and landscape restoration	**(19 - 36)**
The role of nutrient availability and resorption efficiency and their impact on nutrient conservation in mangroves	**(37 - 52)**
Phenol solutions recovery as water pollutants with eugenol cross-linked diallyl phthalate using supported liquid membrane	**(53 - 70)**
Impacts of environmental quality and employment resilience during the coronavirus disease 2019 recession and recovery	**(71 - 88)**
Nine circular strategy approach for the sustainable management of waste in the palm oil industry	**(89 - 104)**
Municipal panel data analysis for solid waste, local governments and citizen participation	**(105 - 122)**
Characterization of shallow groundwater in coastal aquifer of urbanized area using stable isotope and hydrochemical approaches	**(123 - 136)**
Environmentally friendly synthesis of nanoporous silica materials using quercetin as a morphogenetic agent	**(137 - 152)**
Validation of heavy metals in geothermal to support water management practices and mitigation strategies	**(153 – 166)**
Food waste reduction strategies in composting and recycling centers based on material flow analysis	**(167 - 180)**
Conversion of motorcycles to electric vehicles towards sustainable mobility	**(181 - 200)**
A statistical approach to the water scarcity implications on food security	**(201 - 218)**
Exploring the potential of palm oil plantation waste for local communities using mixed methods	**(219 - 236)**
Bibliometric analysis of biochar application for environmental management in agricultural sector	**(237 - 250)**
Radiation hazards from natural radionuclides contained in rice from former tin mining land	**(251 - 262)**
Utilization of agricultural waste to reduce enteric methane emissions on livestock in tropical environment	**(263 - 278)**
Sustainability index for eco-friendly cattle farming in dry climate regions	**(279 - 302)**
Spatial planning strategies and community behavior towards flood control	**(303 - 322)**
Intervention strategy for sustainable waste management systems in developing countries using community of practice	**(323 - 348)**