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ORIGINAL RESEARCH ARTICLE

Cerbera odollam extracts as eco-friendly botanical insecticides against *Arthroschista hilaralis* Walker

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ABSTRACT

BACKGROUND AND OBJECTIVES: Arthroschista hilaralis Walk. is an insect pest that poses a significant threat to Neolamarckia cadamba trees, adversely affects plant growth, and potentially causes death in severe attacks. The current study examines how botanical insecticides can serve as an eco-friendly approach to pest management, with a specific focus on Cerbera odollam. This study aimed to assess the insecticidal effectiveness of methanol extracts and n-hexane fractions from Cerbera odollam leaves and seeds against Arthroschista hilaralis larvae and identify the bioactive compounds responsible for the insecticidal effects.
METHODS: This study assessed the toxicity of methanol extracts and n-hexane fraction derived from Cerbera odollam leaves and seeds against second and third-instar larvae of Arthroschista hilaralis. Laboratory and nursery bioassays were conducted using three concentrations: 0.25 percent, 0.5 percent, and 0.75 percent alongside a control group to assess mortality and developmental inhibition of Arthroschista hilaralis larvae. Active compounds were identified through phytochemical screening and gas chromatography-mass spectrometry analysis. Mortality, pupation, and adult emergence data were analyzed using probit analysis to estimate lethal concentration 50 and lethal concentration 95 values.
FINDINGS: After 72 hours of exposure, the lethal concentration 50 values of methanol seed and leaf, and n-hexane seed and leaf on the second instar were 0.44, 0.64, 0.40, and 0.52 percent, respectively. While on the third instar were 0.52, 0.64, 0.44, and 0.57 percent, respectively. The n-hexane fraction of Cerbera odollam seed extracts was the most effective in inducing Arthroschista hilaralis larval mortality. The n-hexane fraction, measuring between 0.5 and 0.75 percent from Cerbera odollam seeds, led to an 80 to 100 percent mortality rate in second and third-instar larvae. The n-hexane fraction of Cerbera odollam seeds extended the pupal development period by 2.0 to 2.67 days compared to the control group. Cerbera odollam leaf and seed extract contains significant chemical substances that are biologically active, including fatty acids, phenolic compounds, terpenoids, amines, esters, and hydrocarbons. The main constituents recognized for the insecticidal effects of Cerbera odollam include trans-β-ionone (11.85 percent), acetamide (9.31 percent), and α-copaene (9.61 percent).
CONCLUSION: This study highlights Cerbera odollam, particularly its n-hexane seed fraction, as a highly effective, eco-friendly insecticide against Arthroschista hilaralis. The bioactive elements resulted in full larval death and hindered developmental processes. Supported by nursery trials, Cerbera odollam offers a promising, sustainable solution for integrated pest management in N. cadamba forestry, reducing reliance on synthetic pesticides and supporting environmental conservation.

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INTRODUCTION

Neolamarckia cadamba (Roxb.) Bosser, commonly known as jabon, is a fast-growing evergreen tree from the Rubiaceae family, native to south and southeast Asia, particularly Indonesia (Yuan *et al.,* 2020; Velidandi *et al.,* 2023; Singh *et al.,* 2023). This versatile tree provides raw materials for various products such as paper, fiberboard, plywood, boxes, chests, toys, carvings, and pencils. Additionally, *N. cadamba* is recognized as an excellent biomass resource (Richardson *et al.,* 2020; Yadav *et al.,* 2022; Suhaya *et al.,* 2023). Beyond its industrial applications, *N. cadamba* demonstrates diverse pharmacological activities, such as analgesic, anti-inflammatory, anti-helminthic, antibacterial, and antidiabetic effects (Sharma and Khandelwal, 2023; Kumar *et al*., 2023). Another significant issue in the cultivation of *N. cadamba* is the invasion of insect pests, which negatively affect tree growth and overall vitality, causing considerable financial setbacks. Species within the order Lepidoptera, including moths, skippers, and butterflies, play essential roles in forest and agricultural ecosystems. (Utami *et al.,* 2018; Thu *et al*., 2021). Chung *et al*. (2019) identified 13 lepidopteran species associated with *N. cadamba*. *Arthroschista hilaralis* Walker (Lepidoptera: Pyralidae) has been identified as a major pest that affects species in both nursery and field environments (Utami *et al*., 2018; Suetsugu *et al*., 2018; Utami, 2018; Thu *et al*., 2021). *A. hilaralis* larvae consume a significant amount of young jabon leaves, with documented infestation levels reaching as high as 74 percent (%) 74% and defoliation rates surpassing 50% in 2-year-old stands during the rainy season (Suetsugu *et al*., 2018; Utami *et al*., 2018; Hasan *et al.,* 2021). Seedlings in nurseries are particularly susceptible to damage, frequently experiencing complete defoliation within a few weeks following initial infestation (Susanty *et al*., 2017; Utami, 2018). The pest has a life cycle that is relatively short, spanning around 25-26 days, and demonstrates a high reproductive capability, yielding over 70 offspring for each female, contributing to quick population expansion and frequent outbreaks (Susanty *et al*., 2017; Utami *et al*., 2018). *A. hilaralis* poses major challenges to jabon plantations and forestry ecosystems, leading to significant economic losses (Suetsugu *et al.,* 2018; Thu *et al*., 2021; Yadav and Singh, 2023). Consequently, a range of management strategies have been put into action, with chemical control being the foremost approach to lower its populations. However, the excessive use of synthetic insecticides has caused pest resurgence, resistance, secondary pest outbreaks, environmental pollution, and harm to non-target organisms (Serrao *et al*., 2022; Lull *et al.,* 2023; Koswanudin *et al*., 2025). The resistance to diamide insecticides, the primary class of chemicals utilized to target lepidopteran pests, has been well-documented (Richardson *et al*., 2020).These challenges have prompted a growing interest in alternative pest management approaches that reduce reliance on conventional pesticides while maintaining effective control. Botanical insecticides serve as effective and sustainable solutions for pest control, minimizing ecological harm and the likelihood of resistance emergence. While they may require more frequent application than synthetic insecticides, their lower toxicity and reduced environmental and health costs can make them cost-effective in large-scale forestry. Integrated into pest management strategies, they support sustainable yield protection with fewer long-term risks. *Cerbera odollam* Gaertn (Apocynaceae family) is native to tropical regions of Asia, Australia, Madagascar, and the Western Pacific islands (Suhaya *et al*., 2023; Chattopadhyay, 2023). This species comprises bioactive phytochemicals that have proven to be effective as bioinsecticides targeting both urban and agricultural pest populations (Rosalina *et al.,* 2016; Tarmadi *et al*., 2018; Saxena *et al*., 2023). Cerberin, a steroidal metabolite in *C. odollam* fruit seeds and peels, acts as an insect repellent and induces anorexia in insect larvae (Meisyara *et al*., 2020; Saxena *et al*., 2023; Ilmiawati *et al*., 2024). Various elements of *C. odollam*, comprising seeds, fruit tissue, branches, bark, and leaves, have been documented to exhibit insecticidal effects on numerous pest species (Saxena *et al*., 2023; Ilmiawati *et al*., 2024). Bioassay techniques utilized for the extraction of *C. odollam* commonly employ methanol, n-hexane, and ethyl acetate as solvents. These approaches are intended to determine the existence of bioactive elements that could have insecticidal properties. Previous study has demonstrated the effectiveness of solvents such as methanol, n-hexane, and ethyl acetate in extracting insecticidal compounds from various plant species (Pavela, 2016; Saleem *et al.,* 2024). These solvents have proven to be effective in isolating a diverse array of bioactive constituents. Methanol

leaf derived from *C. odollam* have exhibited lethal effects on *Spodoptera litura* (Purwani *et al*., 2017), while seed extracts cause notable larval mortality in *Aedes aegypti* and *Culex quinquefasciatus*, outpacing other parts of the plant (Tarmadi *et al*., 2018; Meisyara *et al*., 2020). Furthermore, *C. odollam* has exhibited notable insecticidal efficacy against various pests, including the termite species *Captotermes curvignathus* (Rosalina *et al.,* 2016), *Aphis gossypii* (Santi *et al*., 2022), and *Riptortus linearis* (Haryanta *et al*., 2020). The n-hexane extract of *C. odollam* had a significant effect on *Spodoptera frugiperda* pests, the extract caused larval mortality of up to 92% at a concentration of 1.46%, and an lethal concentration 50 (LC_{50}) of 0.246% in 72 hours (h) (Arizona *et al.,* 2023). *C. odollam* serves multiple purposes, encompassing its medicinal attributes and its application as a natural pesticide in farming (Saxena, 2023). The wide distribution of *C. odollam* ranging from Asia, Australia, Madagascar, and the islands of the Western Pacific Ocean, can support the availability and sustainability of the intended biopesticide production (Ogunnupebi *et al.,* 2020; Moruzzo *et al.,* 2021; Saxena *et al.,* 2023). Consequently, the current study intends to explore the insecticidal potency of methanol extracts and n-hexane fractions sourced from *C. odollam* leaves and seeds against *A. hilaralis* larvae. This involved determining the lethal concentration 50 for each extract type against second- and third-instar *A. hilaralis* larvae and examining the chemical compounds with potential insecticidal properties. This study was conducted at the Environment and Forestry Research and Development Institute in Palembang, South Sumatra, Indonesia in 2022.

MATERIALS AND METHODS

Rearing of A. hilaralis

Larvae of *A. hilaralis* were collected from 1- to 2-year-old *N. cadamba* trees in Sukatani Village, Banyuasin Regency, South Sumatra, Indonesia, and subsequently reared under controlled laboratory conditions. The larvae were placed in plastic containers measuring 28 centimeters (cm) × 20 cm × 6 cm equipped with gauze-covered windows and stencil paper lids for ventilation. They were fed fresh young *N. cadamba* leaves, which were replaced daily. To achieve ideal humidity and minimize overcrowding, each container was designed to hold 20 to 30 individuals. Prior to pupation stage, sterile sawdust was placed at the base of the container to support the pupation process. The resulting pupae were transferred to smaller containers (7 cm high × 10 cm diameter) for the emergence of adults. Emerged adults were given a 10% honey solution on cotton as a food source, and *N. cadamba* leaves were inserted into water-filled film bottles as oviposition substrates. Eggs were harvested and placed into Petri dishes, and the larvae that emerged were nurtured until the second and third instar stages for subsequent bioassay experiments and for further rearing. All rearing procedures were conducted at 25 ± 2 degrees Celsius (°C), with 70 ± 5% relative humidity (RH), and a 12:12 h light-to-dark (L:D) photoperiod.

Preparation of extract

Leaves and mature seeds of *C. odollam* were collected in January 2022 from coastal areas of Banyuasin, South Sumatra, Indonesia. The location was picked for its mangrove impact, which increases the concentration of insecticidal compounds such as cerberin as a result of environmental pressures. Gathering at the seed maturation stage secured maximum phytochemical concentration. *C. odollam* leaves and seeds were dried at ambient temperature for seven days and subsequently ground into a fine powder using a mechanical grinder. The powdered material was subjected to methanolic extraction at 1:10 in weight per volume (w/v), with continuous maceration for 24 h at ambient conditions. Subsequent to extraction, the mixture underwent filtration using a Buchner funnel equipped with Whatman filter paper to isolate the solid residue. The methanolic filtrate was concentrated using a rotary vacuum evaporator to produce the crude extract. The countercurrent distribution method was employed for liquid-liquid partitioning using n-hexane to extract the non-polar fraction. Generally, leaves and seeds are the most frequently used parts because of their high secondary metabolite content and easy extraction. Semi-polar extracts, including ethyl acetate, tend to demonstrate greater toxicity towards insect larvae or eggs, which can vary based on the plant species. The efficacy of biopesticides depends on the polarity of the solvent used in extraction. Polar solvents such as methanol often provide broader biological activity, but non-polar solvents such as hexane are more effective for applications as repellents or fast

contact (Isman, 2020; Tlak Gajger and Dar, 2021). The resulting methanol extracts and n-hexane fractions were kept at 4°C.

Laboratory bioassay

In laboratory tests, the efficacy of *C. odollam* extract was assessed by measuring larval mortality and the inhibition of *A. hilaris* development. The extract was evaluated for its insecticidal activity by testing it on second and third-instar *A. hilaris* larvae. For application, the *C. odollam* extract was formulated as an emulsifiable concentrate (EC) by incorporating 0.1% glycerol phthalate, using a 1:1 ratio of extract to emulsifier. The experiment included three treatment concentrations; 0.25%, 0.5%, and 0.75% along with a control group. Every treatment included 20 larvae and was conducted in triplicate. The larvae were fed using fresh *N. cadamba* leaves as the substrate. The leaves and larvae were placed in glass Petri dishes during the trials. Initially, the leaves were sprayed with the designated treatment solutions and then left to dry at room temperature (28 °C) for 20 minutes. After drying, the *A. hilaris* larvae were sprayed with the same treatment and placed onto the treated leaves. The experimental design followed a completely randomized design (CRD). Mortality data were calculated at 24, 48, and 72 h after treatment (HAT) as the percentage of deaths using Eq. 1 (Prijono *et al.*, 2021):

Larval mortality percentage = number of the death larvae/the total number of larvae × 100% (1)

As stated by Prijono *et al*. (2021), the effectiveness of extracted insecticides can be categorized into various categories as outlined below:

1) mortality (m) ≥ 95% is strong activity, 2) 75%≤ m<95% is relatively strong, 3) 60%≤ m<75% is strong enough, 4) 40%≤m<60% is moderate, 5) 25%≤m<40% is relatively weak, 6) 5%≤ m<25% is weak, and 7) m<5% is not active.

To assess *A. hilaris* development, the experiment utilized three concentrations (0.25%, 0.5%, and 0.75%) and a control group to analyze pupae and adult development. The control group consisted of methanol and n-hexane solvents mixed with an emulsifier (glycerol phthalate, 0.1%) in a 1:1 ratio, aligning with the solvent applied in each extract treatment. The efficacy assessment comprised 20 third-instar larvae at each concentration, with three trials conducted for each. The extract treatments used in this test were the same as those in the mortality test. Treated leaves were provided for 48 h, and the larvae were observed until they developed into pupae and eventually into adults. The pupae percentage formed was calculated using Eq. 2 (Prijono *et al.*, 2021):

Pupae formation percentage = pupae formed/ larvae survived × 100% (2)

The adult formation percentage of was calculated using Eq. 3 (Prijono *et al.*, 2021):

Adult formation percentage = adult emerged / pupae formed × 100% (3)

Nursery bioassay

Trials in the nursery were performed to determine the effectiveness of methanol extracts derived from the seeds and leaves of *C. odollam*. The yield from the methanol extraction was significantly higher at 18.08%, compared to just 8.05% for the n-hexane fraction, indicating superior extraction efficiency. Extracts from both the leaves and seeds of *C. odollam* were tested under nursery conditions at three concentrations: 0.5%, 1.5%, and 2.5%, along with a control. The selection of these concentrations was made based on early laboratory bioassay findings and factors related to crop safety. Higher concentrations were used in the nursery trials to address increased pest pressure, dense plant canopies, and the humid microclimate factors known to reduce spray efficacy. Furthermore, nursery plants exhibit a higher susceptibility to damage, necessitating the use of stronger treatments to guarantee effective pest management and evaluate possible phytotoxicity before wider field deployment. For the trials, 50 second-instar larvae were introduced into an experimental nursery measuring 180 cm in height and 80 cm in width. The top of the structure was covered with paranet mesh to provide sun protection. Each nursery unit contained 20 *N. cadamba* seedlings, which were three months old and ranged from 15 to 20 cm in height. Each treatment was replicated three times. The extracts were applied via foliar spraying 2 and 7 days after larval infestation. The primary response variable recorded was larval mortality, with weekly observations made over a period of four weeks.

Identification of bioactive compound

Phytochemical screening of *C. odollam* extracts (n-hexane fractions and methanol extracts) was conducted using standard protocols as described by Harborne (1987). Gas chromatography-mass spectrometry (GC-MS) analysis was applied to identify bioactive components. It was conducted on the extract and revealed the most significant insecticidal activity in prior bioassays. Sample preparation involved dissolving the extract in 15 milliliters (mL) of distilled water. The solution was analyzed using a Shimadzu GC MS Quadrupole (GC MS-QP) 2010 system. The GC-MS was operated under temperature conditions ranging from 50 °C to 280 °C, with a total runtime of 37.5 minutes. Throughout the run, spectral data were collected, which facilitated the identification of compounds based on molecular weight and fragmentation patterns.

Data analysis

Lethal concentration values (LC_{50} and LC_{95}) were calculated using probit analysis with the PoloPlus software (Robertson *et al*., 2003). A one-way analysis of variance (ANOVA) was utilized to assess how extract concentration affects larvae mortality and developmental parameters. If significant differences were found ($p < 0.05$), treatment means were compared using Duncan's multiple range test (DMRT). The statistical analysis system (SAS) software, version 9.1, was conducted in all statistical analyses.

RESULTS AND DISCUSSION

Synthetic pesticides' ecological and health risks highlight the urgent need for practical, plant-based alternatives in forest pest management. Another viable choice is to utilize plant extracts, as they break down more easily and contribute very little pesticide residue to the environment. These botanical insecticide extracts break down quickly on plant surfaces due to sunlight, rain, and microbial activity exposure. Research on pesticide residues shows that azadirachtin remains effective for 4 to 7 days, pyrethrins for 1 to 2 days, and essential oils often for less than 48 h (Pavela, 2016; Pavela and Benelli, 2016; Isman, 2020). To maintain effective pest control and minimize the risk of residue, it is suggested to reapply these plant-based solutions every 3 to 7 days, given their short persistence (Ogunnupebi *et al.*, 2020, Isman, 2020). Mitigating *A. hilaralis* infestations is crucial for *N. cadamba*, an important forestry commodity in Indonesia (Fig. 1). This study examined the insecticidal effects of *C. odollam* leaf extract on *A.*

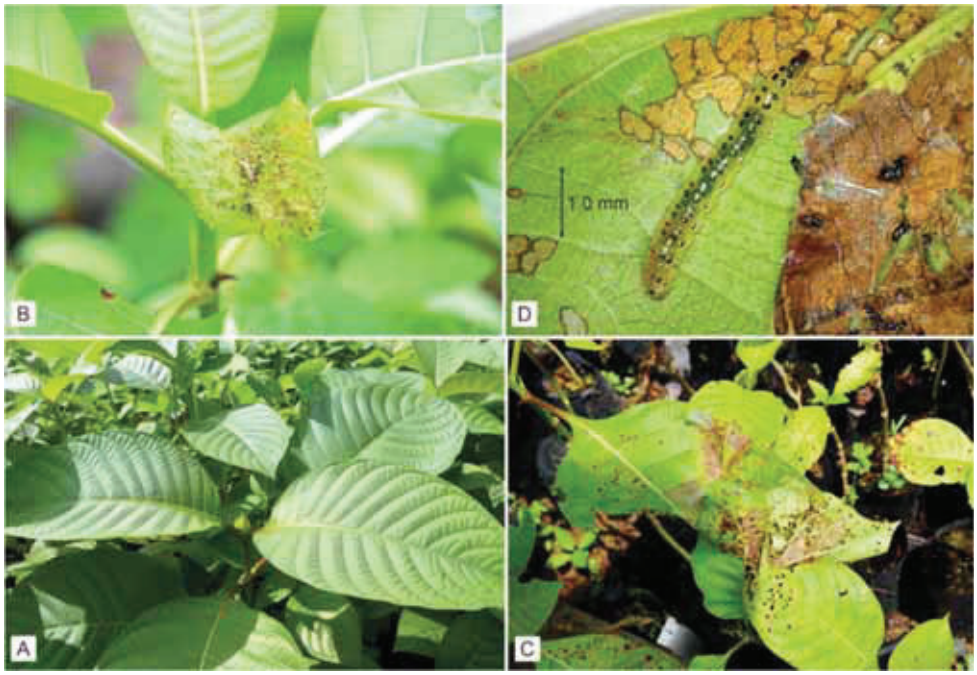

Fig. 1: Symptoms of *Arthroschista hilaralis* infestation on *Neolamarckia cadamba* seedlings: (A) Healthy seedling; (B, C) Foliar damage; (D) Second instar larva

hilaralis larvae feeding on *N. cadamba*. An in-depth analysis of the constituents of the extract highlighted essential bioactive compounds that contribute to its effective larvicidal properties. This mechanistic perspective not only improves comprehension of its mode of action but also highlights its potential as a viable and sustainable pest management agent.

Mortality rates

The data shows that as the concentration of the extract increases, along with the type and the plant part used, larval mortality significantly escalates. Statistical analysis demonstrated that solvent type, plant part, and extract concentration significantly influenced *A. hilaralis* larval mortality in all instars (Table 1). The n-hexane fractions of *C. odollam* leaves and seeds induced significantly higher mortality than their corresponding methanol extracts. Larval mortality demonstrated a pronounced dose-dependent effect, escalating with elevated levels of methanol extracts and n-hexane fractions. The 0.75% methanol seed extract demonstrated the highest mortality rates in both instars, exceeding the efficacy observed with the leaf extract at the same concentration. Second-instar larval mortality was significantly higher at 0.75% methanolic seed extract compared to 0.5% and 0.25%, with a consistent dose-dependent trend observed across all concentrations. The first, second, and third instars of the early larval stages demonstrate a greater susceptibility to insecticides.. This vulnerability arises from their thinner cuticle, smaller body size, and underdeveloped detoxification enzymes. These physiological features boost the efficacy of botanical insecticides when used at lower doses, resulting in more effective across laboratory and nursery trials (Pavela, 2016; Isman, 2020). Studies on *Spodoptera litura* and *Helicoverpa armigera* indicate that neem and citronella oils demonstrate enhanced effectiveness during the early instar stages (Isman, 2020; Vasantha-Srinivasan *et al.,* 2024).

This study demonstrated that methanol extracts and n-hexane fractions of *C. odollam* exhibited significant insecticidal activity, as evidenced by percentage larval mortality. The mortality rates for second and third-instar larvae fluctuated depending on the type of extract, the specific plant part, and concentration. The extract type is essential in assessing the larvicidal effectiveness. Organic solvents such as methanol generally yield higher larvicidal activity than aqueous extracts, owing to their superior ability to solubilize a broad range of bioactive phytochemicals, including alkaloids, flavonoids, terpenoids, and saponins (Pavela, 2016). Furthermore, the portion of the plant utilized for extraction plays a crucial role in determining the effectiveness of larvicidal activity. Previous studies indicate that different organs of a plant harbor distinct profiles and concentrations of secondary metabolites (Prijono *et al.,* 2021). As an illustration, seeds typically possess higher amounts of

Table 1: Mortality of second- and third-instar *A. hilaralis* larvae 72 HAT with methanol extracts and n-hexane fractions from *C.odollam* leaves and seeds

Type of extract	Concentration (%)	Mortality (%) ± Standard deviation (SD)	
		Second instar	Third instar
Methanol seed	0	0.00 ± 0a	0.00 ± 0a
	0.25	53.89 ± 2.88b	48.33 ± 3.3b
	0.5	82.22 ± 2.67c	73.89 ± 1.92c
	0.75	100.00 ± 0.00d	97.22 ± 1.92d
Methanol leaf	0	0.00 ± 0a	0.00 ± 0a
	0.25	42.22 ± 2.87b	39.44 ± 3.85b
	0.5	60.56 ± 2.51b	55.56 ± 1.45c
	0.75	86.67 ± 2.46c	86.11 ± 3.84d
n-hexane seed	0	0.00 ± 0a	0.00 ± 0a
	0.25	70.56 ± 2.86b	60.56 ± 1.95b
	0.5	85.56 ± 2.88c	80.56 ± 5.77c
	0.75	100.00 ± 0.00d	100.00 ± 0.00d
n-hexane leaf	0	0.00 ± 0a	0.00 ± 0a
	0.25	58.89 ± 2.46b	53.33 ± 2.45b
	0.5	67.22 ± 5.77b	61.11 ± 0c
	0.75	100.00 ± 0.00c	98.33 ± 5.09c

Remarks: Means followed by the same letter within a column are not significantly different (DMRT, $p > 0.05$)

harmful substances in comparison to leaves. However, the effectiveness of these parts is also influenced by the extract type, highlighting the importance of a synergistic approach in determining the most suitable extract-plant part combination. The concentration of plant extract used is another key determinant of larvicidal efficacy. A clear correlation exists between dosage and effect, with rising concentrations causing greater mortality in larvae (Purwani *et al.,* 2017). These factors underscore the importance of an integrated, multi-variable approach to applying botanical larvicides to optimize pest management strategies. Following the criterion proposed by Prijono *et al.* (2021), an extract is considered adequate if it induces at least 80% larval mortality. In this context, the n-hexane fractions showed superior efficacy to methanol extracts, with methanol and n-hexane seed extracts meeting the threshold for effective insecticides. The fast-acting larvicidal response and developmental interference noted following the application of n-hexane seed extracts can be linked to various synergistic mechanisms. These mechanisms deliver potent, fast-acting toxicity within 72 HAT. The lipophilic compounds found in the hexane fractions influence the insect cuticle and cell membranes, destabilizing their structural integrity and altering their permeability. This action causes cell lysis, leading to a disruption of neuronal and metabolic functions almost immediately (Abbas *et al.,* 2023). Vasantha-Srinivasan *et al.* (2024) reported that larvae exposed to these extracts experience epithelial cell degeneration, damage to microvilli, and disruption of the peritrophic membrane in the midgut. These effects obstruct adequate digestion and nutrient assimilation, hinder growth, and could potentially result in cell death. Additionally, the alkaloids and terpenoids present in the seed extract inhibit key neuroenzymes such as acetylcholinesterase (AChE), causing an accumulation of acetylcholine in synapses. This accumulation results in overstimulation, paralysis, and ultimately results in the death of the larvae (Isman, 2020; Popescu *et al.,* 2021; Vasantha-Srinivasan *et al.,* 2024). These findings highlight its promise as a natural alternative for pest control in agriculture. Several studies indicate that *C. odollam* has potential as a botanical insecticide due to its effectiveness against pests such as *Aphis gossypii* (Santi *et al*., 2022), *Spodoptera litura* (Purwani *et al*., 2017), and *Captotermes curvignathus* (Rosalina *et al.,* 2016). Moreover, the n-hexane fraction of *C. odollam* seeds exhibits potent biopesticidal activity, causing high larval mortality in *Culex quinquefasciatus* (Meisyara *et al*., 2020) and *Aedes aegypti* (Wong *et al*., 2024). Second-instar *A. hilaralis* larvae exhibited a higher sensitivity to *C. odollam* extract treatments compared to third-instar larvae. Across all extract treatments, the average mortality of second-instar larvae consistently exceeded that of third-instar larvae. As an illustration, the application of the n-hexane fraction from seed extracts led to increased mortality rates in second-instar larvae compared to third-instar larvae under the same conditions. The methanol extract of *C. odollam* induced mortality rates ranging from 42.22% to 100% in second-instar larvae and 39.44% to 97.22% in third-instar larvae. Likewise, the n-hexane fractions obtained from seeds and leaves produced mortality rates between 58.89% and 100% for second-instar larvae, and 53.33% to 100% for third-instar larvae. The leaf extract of *C. odollam* demonstrated low insecticidal activity at a 0.5% concentration, with mortality rates of 38.33% for second-instar larvae and 36.67% for third-instar larvae. Consistent with Kaur *et al.* (2019) and Prijono *et al.* (2021), extracts with less than 50% efficacy at this concentration are generally deemed unsuitable for further development because of economic inefficiency. Furthermore, they may introduce ecological threats, which encompass phytotoxic effects and detrimental impacts on helpful natural enemies like egg parasitoids. In addition, *C. odollam* is known to exhibit extremely potent toxic effects that can lead to serious health risks for humans. Poisoning symptoms can manifest as nausea, vomiting, irregular heartbeat, dysfunction of organelles, myocardial infarction, thrombocytopenia, dilated pupils, and bradycardia (Menezes *et al.,* 2018, Bernshteyn *et al.,* 2020; Saxena *el al.,* 2023). Conversely, the methanol and n-hexane seed fractions exhibited considerable larvicidal activity against *A. hilaralis* within 72 hours, indicating their potential as effective biopesticides.

In general, second-instar *A. hilaralis* larvae exhibited higher mortality at 24 HAT compared to later time points (Fig. 2). The highest mortality in second-instar larvae was recorded with the 0.75% concentration of the seed n-hexane fraction. Simultaneously, the lowest concentration was noted with the 0.25% concentration of the methanol leaf extract. For third-instar larvae, mortality also peaked

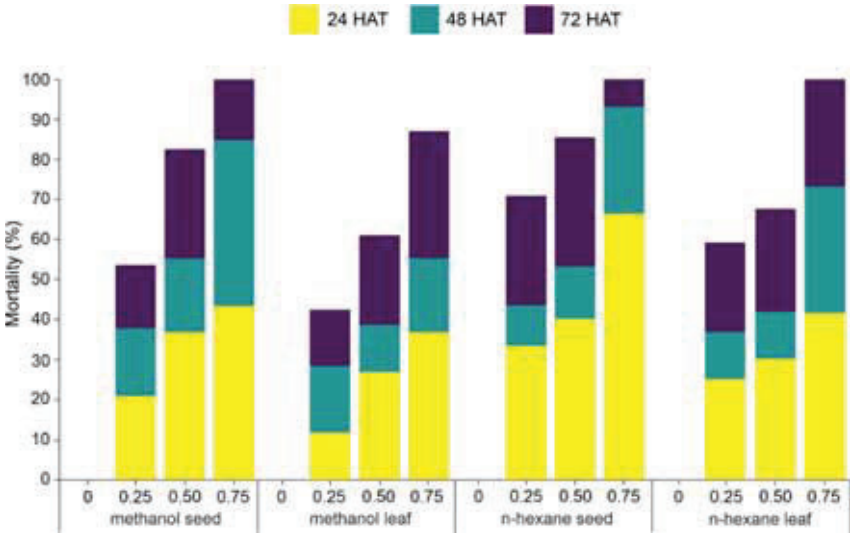

Fig. 2: Mortality rate of second instar *A. hilaralis* larvae at 24, 48, and 72 HAT

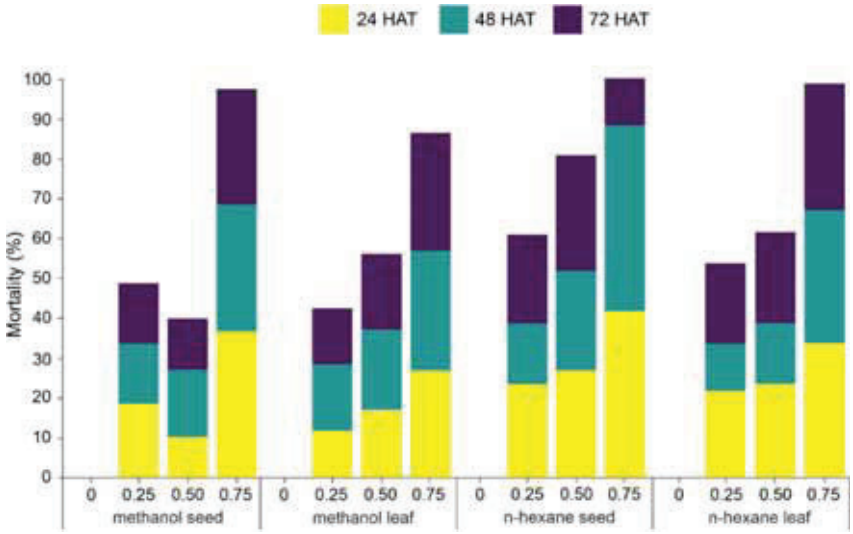

Fig. 3: Mortality rate of third instar *A. hilaralis* larvae at 24, 48, and 72 HAT

at 24 HAT. At 48 HAT, the peak mortality was recorded with 0.75% concentrations of the methanol leaf extract and the seed n-hexane fraction (Fig. 3). Probit analysis confirmed the potency of seed-derived extracts: LC_{50} and LC_{95} values for second-instar larvae were 0.40% and 0.82%, while for third-instar larvae, they were 0.44% and 0.88% (Table 2). Second-instar larvae exhibit a marginally higher susceptibility than third-instar larvae, emphasizing the enhanced effectiveness seed-based formulations utilizing the higher efficacy of seed-based formulations of the methanol extract and n-hexane fraction. Probit analysis showed that 0.40% and 0.44% concentrations of *C. odollam* seed n-hexane fraction caused 50% mortality (LC_{50}) in second and third-instar *A. hilaralis* larvae. The LC_{95} value of the seed fraction from *C. odollam* against instars 2 and 3 larvae of *A. hilaralis* is less than 1%. This finding underscores its significant

Table 2: Estimator of toxicity parameters of *C. odollam* extract against *A. hilaralis* second and third instar after 72 h of exposure.

Test extract	N	a ± SE	b ± SE	LC50 (%)	95% CI		LC95 (%)	95% CI	
					Lower	Upper		Lower	Upper
Second instar									
Methanol seed	20	-1.56 ± 0.19	3.56 ± 0.40	0.44	0.38	0.49	0.90	0.80	1.05
Methanol leaf	20	0.03 ± 0.04	1.10 ± 0.08	0.64	0.56	0.76	1.34	1.12	1.74
n-hexane seed	20	-1.60 ± 1.20	3.97 ± 0.43	0.40	0.35	0.45	0.82	0.73	0.95
n-hexane leaf	20	-1.50 ± 0.19	2.88 ± 0.37	0.52	0.46	0.59	1.09	0.95	1.33
Third instar									
Methanol seed	20	-1.47 ± 0.19	2.83 ± 0.37	0.52	0.46	0.59	1.10	0.95	1.34
Methanol leaf	20	-1.58 ± 0.20	2.47 ± 0.38	0.64	0.56	0.76	1.31	1.10	1.68
n-hexane seed	20	-1.62 ± 0.20	3.72 ± 0.42	0.44	0.38	0.49	0.88	0.78	1.02
n-hexane leaf	20	-1.52 ± 0.19	2.67 ± 0.37	0.57	0.50	0.66	1.19	1.02	1.47

N= number of *A. hilaralis* larvae used in experiment, a = probit regression intercept, b = probit regression slope, SE = standard error, CI = confidence interval

potential as a commercial botanical insecticide, due to its strong insecticidal efficacy. It suggests that bioactive compounds present in *C. odollam* possess potent insecticidal properties. The duration to reach lethal outcomes is contingent upon several factors, including the specific insecticidal compound, the species and life stage of the target insect, the amount administered, the technique of application, the surrounding environmental conditions, and the behavior of the insect (Watanabe, 2015; Pavela and Benelli, 2016; Sohrabi *et al*., 2019).

Inhibition activity in the formation of pupa and adult

Third instar larvae of *A. hilaralis* exposed to methanol extracts and n-hexane fractions of *C. odollam* leaves and seeds showed incomplete mortality after 48 h. As a result, the larvae continued to develop into the pupal stage. The percentages for pupation and adult emergence averaged significantly differently among treatments that employed various extract types. In the control group, pupae and adult formation reached 100%. Nonetheless, enhancing the concentration of *C. odollam* extracts, irrespective of the solvent type or the plant part utilized, caused a notable decline in the percentages of pupation and adult emergence. Notably, the n-hexane seed and leaf fractions at a concentration of 0.75% completely inhibited pupal and adult formation. Furthermore, greater extract concentrations correlated with longer developmental durations for pupae and adults (Table 3). The average time required for pupation and adult emergence in the control group was 4 and 6 days, respectively. In comparison, larvae subjected to 0.75% n-hexane seed fraction exhibited a three-day postponement in pupation and the emergence of adults, highlighting a pronounced inhibitory effect. Conversely, the extract of methanol leaf at 0.25% exerted the weakest inhibitory effect, with only modest delays of one day for pupation and two days for adult emergence. These results imply that elevated concentrations of the n-hexane seed fraction hinder the emergence of pupae and adults, as well as postpone development in *A. hilaralis*.

Remarks: Means followed by the same letter within a column are not significantly different (DMRT, $p > 0.05$)

The study emphasizes the effectiveness of *C. odollam* seed extracts, particularly those derived using n-hexane, in disrupting the life cycle of *A. hilaralis*. Plant-derived insecticides are recognized for their effectiveness in repelling insects, suppressing feeding activities, and disrupting growth and development. The disruption of insect growth, especially during the shift from pupal and adult phases, plays a crucial approach in pest control (Pavela, 2016; Isman, 2020). Botanical insecticides, rich in bioactive compounds, can inhibit these developmental stages, thereby reducing successful metamorphosis. This study highlights the significance of *C. odollam* extracts in influencing not just larvae but also pupae and adults, demonstrating a lasting effect of the treatment. The larvicidal mechanisms of cerberin, a key compound in *C. odollam*, involve inhibition of the sodium/potassium adenosine triphosphatase (Na^+/K^+-ATPase) enzyme. This inhibition disturbs the balance of ions, resulting in compromised nerve and muscle function, and ultimately causing extensive cellular death. In contrast, saponins act by lysing cell membranes

Table 3: Percentage of pupation and adult emergence of *A. hilaralis* under botanical extract treatments

Type of extract	Concentration (%)	pupae formed (% ± SD)	adults emerged (% ± SD)	Development time (days ± SD)	
				pupae	adults
Methanol seed	0	100.00 ± 0.00a	100.00 ± 0.00a	3.67 ± 0.58a	6.33 ± 0.58a
	0.25	70.21 ± 2.06b	86.77 ± 4.08b	5.33 ± 0.58b	7.67 ± 0.57b
	0.5	33.69 ± 7.69b	55.56 ± 4.81b	5.67 ± 0.58b	8.00 ± 0.00b
	0.75	8.33 ± 2.06b	0.00 ± 0.00b	6.00 ± 0.00b	8.33 ± 0.35b
Methanol leaf	0	100.00 ± 0.00a	100.00 ± 0.00a	3.67 ± 0.58a	6.67 ± 0.35a
	0.25	92.09 ± 3.61b	94.19 ± 4.63a	5.00 ± 0.00b	7.67 ± 0.57b
	0.5	88.89 ± 8.52b	86.90 ± 5.77a	5.33 ± 0.57b	8.00 ± 0.33b
	0.75	50.00 ± 1.61b	58.33 ± 1.37b	5.67 ± 0.55b	8.00 ± 0.55b
n-hexane seed	0	100.00 ± 0.00a	100.00 ± 0.00a	3.66 ± 0.58a	6.33 ± 0.57a
	0.25	69.84 ± 3.33b	47.22 ± 6.41b	6.00 ± 0.00b	8.00 ± 0.58b
	0.5	22.22 ± 5.09b	33.33 ± 12.22b	6.33 ± 0.57b	8.33 ± 0.58b
	0.75	0.00 ± 0.00c	0.00 ± 0.00c	7.00 ± 0.00c	8.67 ± 0.73c
n-hexane leaf	0	100.00 ± 0.00a	100.00 ± 0.00a	3.67 ± 0.57a	6.33 ± 0.57a
	0.25	84.13 ± 3.96b	94.44 ± 5.13ab	5.56 ± 0.53b	7.67 ± 0.57ab
	0.5	68.61 ± 2.96b	75.56 ± 7.21ab	6.23 ± 0.58b	7.67 ± 0.57ab
	0.75	16.67 ± 17.26c	33.33±26.46b	6.66 ± 0.55b	8.00 ± 0.53b

in the larval digestive tract. Additionally, tannins contribute to the damage of the intestinal epithelial lining (Isman, 2020; Popescu *et al.,* 2021). These phytochemicals affect insect physiology through multiple pathways, underscoring their potential in integrated pest management. In this study, *C. odollam* extracts significantly inhibited pupation and adult emergence, while also prolonging the duration of these developmental stages. These effects are likely attributable to specific bioactive compounds present in the seeds. Steroidal compounds in the extracts may disrupt insect molting due to their structural similarity to ecdysteroids, the hormones that regulate molting and metamorphosis in insects (Watanabe, 2015; Menezes *et al.,* 2018; Meisyara *et al.,* 2020). By imitating or disrupting these hormonal signals, plant-based steroids can impede larval growth. Tannins further assist by attaching to proteins within the insect's digestive tract, which negatively affects nutrient absorption and lowers the effectiveness of digestive enzymes such as protease and amylase (El-Aswad *et al.,* 2022; Wong *et al.,* 2024). This interference likely compromises larval nutrition and delays metamorphosis. Steroids in the seed extracts are further recognized for their molting-disruptive effects, again due to their mimicry of ecdysteroids (Tarmadi *et al.,* 2018; Saxena *et al.,* 2022). Cerberin, in particular, interferes with calcium ion channels in larvae, leading to altered heart rates and anorexia (Rosalina *et al.,* 2016; Menezes *et al.,* 2018). Recent studies have substantiated its cardiotoxicity via the inhibition of calcium ion movement in heart tissues, which disrupts circulation and raises larval mortality rates (Wong *et al.,* 2024). In addition to cerberin and steroids, *C. odollam* seeds contain alkaloids known for their repellent and antifeedant properties, which contribute to their broad-spectrum insecticidal activity (Rosalina *et al.,* 2016; Tarmadi *et al.,* 2018; Kaur *et al.,* 2019). The presence of saponins in the seeds further jeopardizes the integrity of larval bodies by disrupting the permeability of cell membranes, enabling toxins to infiltrate. They also inhibit acetylcholinesterase activity, which can cause neuromuscular disruptions such as muscle spasms and paralysis (Beaumelle *et al.,* 2023; Ilmiawati *et al.,* 2024). The methanol extract and n-hexane fraction from *C. odollam* seeds show significant insecticidal activity against *A. hilaralis* larvae, highlighting their potential for sustainable pest control.

Nursery bioassay

An evaluation of the insecticidal efficacy of methanol extracts from the seeds and leaves of *C. odollam* was performed in a nursery trial, focusing on both the yield of the extracts and the trends in larval mortality over a period of time. The methanol extraction process yielded significantly more extract (18.08%) compared to the n-hexane fraction (8.05%), indicating a higher extraction efficiency. Owing to its low yield, the n-hexane fraction was excluded from

Table 4: Mean mortality of *A. hilaralis* larvae treated with *C. odollam* leaf and seed extracts in the *N. cadamba* nursery environment

Extract type	Concentration (%)	N sample	Mortality (%) on week ± Standard error (SE)				
			I	II	III	IV	Total
Methanol leaf	0	50	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00c	0.00 ± 0.00c
	0.50	50	10.00 ± 0.00b	8.00 ± 1.15a	8.00 ± 1.15b	4.67 ± 0.67b	30.67 ± 1.76c
	1.50	50	11.33 ± 1.33b	13.33 ± 0.66b	12.67 ± 1.33ab	14.00 ± 1.15a	51.33 ± 1.76b
	2.50	50	18.00 ± 1.15a	16.00 ± 1.15a	16.00 ± 1.15a	14.67 ± 0.67a	64.67 ± 0.67a
Methanol seed	0	50	0.00 ± 0.00c	0.00 ± 0.00d	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c
	0.50	50	10.67 ± 1.76b	10.00 ± 1.15b	13.33 ± 0.67b	12.00 ± 2.30b	46.00 ± 2.30b
	1.50	50	22.00 ± 1.15a	15.33 ± 1.33b	21.33 ± 1.33a	16.67 ± 0.67ab	82.00 ± 0.67a
	2.50	50	24.67 ± 0.67a	22.00 ± 1.15a	22.67 ± 1.76a	23.33 ± 1.76a	86.00 ± 1.76a

Remarks: Means followed by the same letter within a column are not significantly different (DMRT, $p > 0.05$).

semi-field testing. Larval mortality of *A. hilaralis* was monitored weekly over four weeks following treatment with varying concentrations of the methanol extracts (Table 4). The control groups (0% concentration) showed no mortality, indicating that the environmental conditions did not lead to larval death. The methanol extracts from both seeds and leaves exhibited concentration-dependent increases in larval mortality. The methanol leaf extract induced mortality ranging from 30.67 ± 1.76% at 0.50% concentration to 64.67 ± 0.67% at 2.50%. The weekly mortality figures indicated that the peak rates were recorded in weeks III and IV, particularly at elevated concentrations, implying a potential delayed or cumulative toxic effect. In contrast, the methanol seed extract demonstrated substantially greater efficacy. At 0.50% concentration, mortality reached 46.00 ± 2.30%, escalating to 82.00 ± 0.67% and 86.00 ± 1.76% at 1.50% and 2.50%, respectively. The highest weekly mortality, 23.33 ± 1.76%, was recorded during week IV at the 2.50% concentration. Statistical analysis confirmed significant differences among treatments, with the 2.50% seed extract consistently resulting in the highest mortality. These observations underscore the enhanced insecticidal capability of *C. odollam* seed extracts relative to leaf extracts for the control of *A. hilaralis* larvae in nursery environments. The enhanced performance of the seed extract is consistent with previous studies demonstrating greater pesticidal activity in seed-derived botanical materials. For instance, Kumar *et al.* (2016) reported that cinnamoyl amides isolated from *Zanthoxylum armatum* were effective larvicides against *Plutella xylostella*. Similarly, tannins from *Camellia sinensis* and *Urtica dioica* significantly inhibited larval growth in *Spodoptera littoralis* (El-Aswad *et al.,* 2022). The steady escalation in mortality recorded over successive weeks, notably at increased concentrations, implies a potential for lasting or cumulative toxicity, which is advantageous for prolonged pest management. Among all treatments, the 2.50% methanol seed extract emerged as the most effective, achieving up to 86% mortality, thereby underscoring its promise as a natural biocontrol agent. Further investigation is needed to pinpoint and characterize the bioactive compounds that contribute to the observed larvicidal effects, clarify their mechanisms of action, and evaluate their environmental safety. Although the precise mechanisms remain to be determined, the data support the development of *C. odollam*-based botanical insecticides for integrated pest management. The study also noted that methanol-based formulations were stabilized using glycerol phthalate (0.1%), which could enhance field applicability due to improved formulation stability. Nevertheless, the present study did not assess how these extracts influence soil microbiota or other components within the nursery. Botanical insecticides, composed of secondary metabolites such as alkaloids, saponins, and terpenoids, may alter soil microbial diversity potentially reducing populations of more sensitive microbes. Conversely, certain extracts have demonstrated the ability to promote advantageous microbial communities, including Azospirillum, Rhizobium, and arbuscular mycorrhizal fungi (Arora *et al.,* 2019). In support of this, Diaz-Martinez *et al.* (2023) demonstrated that botanical insecticides can enhance the activity of critical soil enzymes like dehydrogenase, urease, and phosphatase, all of which contribute to essential nutrient cycling processes. While excessive application of insecticides can disrupt soil microfauna (Beaumelle *et al.,* 2023), botanical insecticides are generally considered environmentally friendly when applied at appropriate concentrations. Their quick breakdown and minimal longevity in the

Table 5: Phytochemical compounds identified in *C. odollam*

Phytochemical compounds	Seed		Leaf	
	Methanol extract	n-hexane fraction	Methanol extract	n-hexane fraction
Alkaloids	+	+	-	-
Flavonoids	-	-	+	+
Tannins	-	-	+	+
Steroids	+	+	+	++
Triterpenoids	+	+	-	-
Saponins	+	+++	-	+

Remarks: (-) not detected; (+) moderate; (++) strong; (+++) very strong

environment render them less detrimental to non-target species like natural predators and parasitoids when compared to synthetic options (Ogunnupebi *et al.,* 2020; Isman, 2020; Saxena *et al.,* 2023). While insect resistance to biopesticides is becoming a growing issue, it generally evolves at a slower pace compared to resistance against chemical pesticides, often via distinct mechanisms. The likelihood of *A. hilaralis* developing resistance to *C. odollam* extracts is relatively low due to the presence of a chemically diverse array of compounds such as phenolics, flavonoids, triterpenoids, and saponins each potentially acting via distinct pathways. This diversity complicates the development of cross-resistance and supports the long-term effectiveness of *C. odollam* extracts in pest management programs. Moreover, integrating *C. odollam* extracts with other botanical insecticides may help mitigate resistance development while enhancing efficacy and sustainability. This holistic strategy provides a viable option to standard pesticides, ensuring effective pest control with limited ecological impact

Bioactive compounds

Phytochemical analysis of the methanol extracts and n-hexane fractions of *C. odollam* (Table 5) revealed the presence of alkaloids, steroids, flavonoids, triterpenoids, tannins, and saponins in both extracts. These plant-derived secondary metabolites collaborate to hinder the growth of insects by influencing multiple physiological systems. Alkaloids interfere with neural transmission (Isman, 2020), while flavonoids inhibit digestive enzymes and enhance bioactivity, particularly when combined with microbial agents (Tlak Gajger and Dar, 2021; Magnani *et al.,* 2025). Tannins bind to digestive enzymes and damage gut tissue, with their effects intensified when paired with flavonoids (El-Aswad *et al.,* 2023). Saponins compromise cell membranes and enhance the absorption of toxins, while steroids and triterpenoids act like insect hormones, leading to a disruption in the molting process (Cui *et al.,* 2019). These combined actions result in a multi-targeted mode of action, increasing insecticidal efficacy and reducing the likelihood of resistance development. GC-MS analysis identified ten major compounds in the seed extract, indicating a rich presence of secondary metabolites. In contrast, the leaf extract contained only ten chemical compounds. Table 6 presents the ten most abundant compounds identified in the seed and leaf extracts of *C. odollam*. Acetamide, a steroidal amide, was the most abundant compound in the seed extract (9.36%), while trans-β-ionone-5,6-epoxide was the predominant compound in the leaf extract (11.86%).

The GC-MS analysis identified ten distinct compounds in the seed extract, reflecting a diverse profile of secondary metabolites. Despite containing ten compounds, the leaf extract demonstrated a lower level of chemical diversity and diminished bioactive potential. Notably, the seed extract included more compounds with established insecticidal properties, indicating higher biological activity than the leaf extract. Among the identified insecticidal compounds were acetamide, trans-β-ionone, and α-copaene secondary metabolites with well-documented insecticidal efficacy against various insect pests. These compounds can collaborate, boosting the total insecticidal efficacy beyond the impact of each separate ingredient. Plant-derived secondary metabolites are known to exhibit synergistic effects on various insect species, making them valuable candidates for botanical insecticide development (Prijono *et al.,* 2021; Cui *et al.,* 2022; Diaz-Martinez *et al.,* 2023). Such synergism interactions frequently cause contact toxicity and, more frequently, slow-

Table 6: Bioactive compounds identified in leaf and seed extracts of *C. odollam* using GC-MS analysis

No	Chemical compound	Relative (%)
	Seed extract	
1	Acetamide, N- [(3. beta.,5. alpha.)-cholestan-3-yl]- (CAS) 3. beta. -Acetamido-5.	9.31
2	2H-1,4-Benzodiazepin-2-one, 7-chloro-1,3-dihydro-5-phenyl-1-(trimethylsilyl)-	6.95
3	Ethyl 4,4-dimethyl-3-(4-methoxyphenyl)-pentanoate	6.66
4	1H-Purin-6-amine, [(2-fluorophenyl) methyl]	6.59
5	Butyric acid	5.84
6	Cyclobuta[1,2:3,4]dicyclooctene, hexadecahydro (6a.alpha.,6b.alpha.,12a.alph	5.59
7	Cyclotetrasiloxane, octamethyl- (CAS) 1,1,3,3,5,5,7,7-Octamethyl-Cycloo	5.57
8	Cyclotrisiloxane, hexamethyl- (CAS) 1,1,3,3,5,5-Hexamethyl-Cyclohexasilo	5.48
9	4,5-epoxy-3,4,6-tri(ethylearbonyloxy)-17-(2-propenyl)morphinane	5.15
10	(7-Isopropylidene-Bicyclo[2.2.1]HEPT-5-EN-2-Ylidene)-Acetic Acid Methyl Ester	5.15
	Leaves extract	
1	Trans-.Beta. -Ionon-5,6-Epoxide	11.85
2	1,2,3,4,5,6-hexamethoxy-hexamethylcyclohexasilane	11.26
3	1,3,5,7-Tetraethyl-1-butoxycyclotetrasiloxane	11.16
4	1,1,3,3,5,5,7,7,9,9,11,11 Dodecamethyl-Hexasiloxane	10.32
5	Tetracosamethylcyclododecasiloxane	9.84
6	Alpha.-Copaene	9.61
7	Silane, 1,4-phenylenebis[trimethyl- (CAS) 1,4-Bis(trimethylsilyl)benzene	9.23
8	4-(3,4-Dimethoxybenzylidene)-1-(4-Nitrophenyl)-3-Phenyl-2-Pyrazolin-5	8.99
9	Dodecamethylhexasiloxane	8.97
10	Estrone Dimethylphosphinic Ester	8.78

acting effects that impede larval growth and affect insect development (Pavela, 2016; Isman, 2020; Cui *et al.,* 2022). Specifically, trans-β-ionone and α-copaene disrupt the development of *A. hilaralis* by targeting the insect's neuroendocrine and digestive systems. Trans-β-ionone interferes with octopaminergic signaling and juvenile hormone pathways, leading to molting disruption and oxidative stress, especially in the early stages of larval development. α-Copaene functions as an antifeedant, impairing gut receptor function and inducing detoxification enzymes, which causes metabolic stress. Both substances also diminish feeding activity and inflict damage on cellular membranes, with larval vulnerability differing according to developmental stage because of physiological differences (Diaz-Martinez *et al.,* 2023; Magnani *et al.,* 2025). Furthermore, Cankaya *et al.* (2025) demonstrated that p-acetamide exhibits larvicidal activity against *Galleria mellonella*, proving lethal at relatively low concentrations. α-Copaene, derived from clove oil, has also effectively controlled the fruit fly *Ceratitis capitata* (Lull *et al.,* 2023).

CONCLUSION

This study highlights the potent insecticidal efficacy of *C. odollam* seed extracts, particularly those obtained using n-hexane, as promising botanical alternatives for controlling *A. hilaralis* a major defoliator of *N. cadamba*. The findings indicate that the effectiveness of larvicidal activity differed markedly according to the type of extract, the specific plant part, the concentration level, and the stage of larval development. The n-hexane seed extract, at a concentration of 0.75%, consistently induced over 80% larval mortality, surpassing the efficacy threshold typically associated with botanical insecticides. This high level of activity underscores the extract's potential for practical application in forestry pest management. Among all treatments, seed-based extracts, irrespective of the type of solvent, demonstrated enhanced insecticidal properties compared to leaf extracts. Notably, the n-hexane seed extract displayed rapid larvicidal effects within 72 h and significantly disrupted *A. hilaralis* development, including decreased pupation and adult emergence rates, as well as extended developmental durations. These insights imply several modes of action that play a role in the extract's effectiveness. In contrast, leaf extracts, particularly at lower concentrations, demonstrated limited efficacy and are thus less suitable for large-scale pest control. Phytochemical screening and GC-MS analysis revealed a diverse array of bioactive compounds in the seed extracts, including flavonoids, steroids, alkaloids, tannins,

triterpenoids, saponins, acetamide, trans-β-ionone, and α-copaene. These substances collaboratively enhance insecticidal effectiveness through a range of physiological mechanisms. The presence of multiple insecticidal agents suggests a synergistic effect that enhances overall bioactivity. Further validation of the laboratory findings was achieved through nursery trials. Although methanol extraction produced a higher crude yield than n-hexane, the n-hexane seed extract proved more potent in terms of rapid toxicity and developmental disruption. The larvicidal activity of the methanol seed extract was notably strong, on par with that of chemical insecticides. Mortality rates increased with concentration and over time, indicating cumulative or delayed physiological effects. The 2.5% methanol seed extract achieved up to 86% mortality by the fourth week, underscoring its efficacy and real-world applicability. The methanol seed extract, which is rich in bioactive elements, influences several pathways, affecting the neuroendocrine and digestive functions in insects. Its biodegradability and low toxicity to non-target organisms further support its integration into eco-friendly pest management strategies. The extract's delayed-action profile is especially advantageous for long-term control within integrated pest management (IPM) systems. Collectively, these findings support the development of *C. odollam* seed-based biopesticides as sustainable alternatives to synthetic pesticides. The extracts' capacity to cause significant mortality, suppress growth, and interfere with metamorphosis in pest larvae positions them as excellent options for environmentally friendly forestry initiatives. However, further research is needed to isolate and characterize the active compounds, optimize extraction processes, and evaluate environmental safety and field performance across diverse ecological settings. Ultimately, *C. odollam* seed extracts particularly those obtained with n-hexane offer a potent, plant-based solution for managing *A. hilaralis* populations. Their varied mechanisms and efficiency emphasize their ability to decrease dependence on synthetic pesticides and encourage sustainable pest control methods in Indonesia and other tropical forest ecosystems.

AUTHOR CONTRIBUTIONS

S. Utami conceptualized the research idea, designed the study, conducted investigations, performed literature reviews, curated data, conceptualized the manuscript, and secured funding. D. Hutapea, design and conceptualize the manuscript, conduct investigations, curate data, perform literature reviews, analyze, and interpret data. G. Pasaribu contributed to the acquisition of data, analysis, interpretation of data, statistical analysis, and manuscript preparation and helped improve the manuscript. I. Guswenrivo participated in conducting investigations, performing literature reviews, acquiring data, analyzing and interpreting data, and drafting the manuscript. D. Koswanudin contributed to performing literature reviews, curating data, performing literature reviews, and obtaining funding. W. Darwiati participated in conducting investigations, performing literature reviews, conceptualizing the manuscript, and securing funding. D. Tarmadi participated in designing the study, conducting investigations, performing literature reviews, acquiring data, analyzing and interpreting data, and drafting the manuscript. H. Siahaan contributed to the acquisition of data, analysis, interpretation of data, and statistical analysis and helped improve the manuscript. T.K. Waluyo contributed to the analysis and interpretation of data and statistical analysis and helped improve the manuscript. M. Wardani performed the literature reviews and statistical analysis and contributed to manuscript preparation. A.H. Lukman performed the literature reviews, drafted the manuscript, and helped improve it. I. B. Rahardjo performed the literature reviews and contributed to manuscript preparation and drafting

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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.

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ABBREVIATIONS

%	Percent
(-)	Not detected
(+)	Moderate
(++)	Strong
(+++)	Very strong
°C	Degree Celsius
µL	Microliters
a	Intercept of probit regression
AChE	Acetylcholinesterase
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
b	Slope of probit regression
CI	Confidence interval
cm	Centimeters
CRD	Completely randomized design
DMRT	Duncan's multiple range test
EC	Emulsifiable concentrate
Fig.	Figure
g	Gram
GCMS	Gas Chromatography-Mass Spectrometry
GCMS-QP	Gas Chromatography-Mass Spectrometry Quadrupole
h	Hours
HAT	Hours after treatment
IPM	Integrated pest management
K^+	Potassium
LC_{50}	Lethal Concentration 50
LC_{95}	Lethal Concentration 95
L:D	Light to dark
m	Mortality
mL	Milliliters
Na^+	Sodium
N	Number of larvae per plant sample
RH	Relative humidity
SAS	Statistical Analysis System
SD	Standard deviation
SE	Standard error
w/v	Weight per volume

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ORIGINAL RESEARCH PAPER

Long-term statistical analysis of rainfall variability for climate adaptation planning in a semi-arid region

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ABSTRACT

BACKGROUND AND OBJECTIVES: Climate variability and changing weather patterns pose increasing challenges to environmental sustainability and resource management. Understanding long-term rainfall trends at the semi-arid regional scale is crucial for developing effective adaptation strategies. This study evaluates precipitation records from 1980 to 2018 to address the limited analysis of rainfall variability in the districts of Madurai and Theni. It identifies temporal trends at seasonal, monthly, and annual scales to improve forecasting and support adaptive climate planning. Data from 21 strategically placed rain gauge stations were analyzed using statistical methods, including the Mann-Kendall test and Spearman's Rank Correlation, to detect shifts in rainfall behaviour and produce actionable insights for local decision-making and climate resilience.

METHODS: Daily rainfall data from Madurai and Theni districts, located between 9°32' and 10°18' north latitude and 77°00' and 78°30' east longitude for Madurai, and between 9°53' and 10°22' north latitude and 77°17' and 77°45' east longitude for Theni, were analyzed over thirty-nine years from 1980 to 2018. Following extensive quality checks, data from twenty-one sites were analyzed for homogeneity and serial correlation. The Cumulative Sum Control Chart and the Modified Mann-Kendall Test, which were supported by the AnClim and trendchange software packages, were used to identify rainfall trends and shifts.

FINDINGS: Rainfall analysis from 1980 to 2018 in Madurai and Theni found 17 of 357 series with serial correlation at 90 percent confidence, notably at Tirumangalam, Usilampatti, Gudalore, and Periyakulam. Annual rainfall increased by 8.56 millimeters per year at Veerapandi, 7.21 millimeters per year at Tiruppuvanam, 5.43 millimeters per year at Edayapatti, 4.87 millimeters per year at Andipatti, 4.52 millimeters per year at Bodi, and 4.11 millimeters per year at Uthamapalayam, but declined by 6.74 millimeters per year at Usilampatti. The corrected Mann-Kendall test showed the strongest trend at Veerapandi (9.02), with weaker trends at Tirumangalam and Usilampatti. Although there were some localized changes, no noteworthy turning points were discovered.

CONCLUSION: This investigation revealed significant seasonal rainfall variability and trend shifts across Madurai and Theni districts. Serial correlation and season-specific trends were identified, with distinct change-points highlighting climatic sensitivity. The study addresses gaps in previous research by providing localized, season-specific insights through integrated trend and change-point analysis. Policy recommendations include promoting drought-resilient crops, enhancing rainwater harvesting, modernizing irrigation. Additionally, incorporating localized rainfall trends into district-level agricultural and water management planning can support adaptive responses to evolving rainfall patterns in southern Tamil Nadu.

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INTRODUCTION

Rainfall plays a crucial role in the hydrological cycle, influencing various aspects of human society, including its substantial impact on agricultural activities, hydropower generation, the phenology of vegetation, and the overall sustainability of biodiversity (Jain and Singh 2020; Bakure *et al.,* 2022). Precipitation that is both sufficient and timely is critical for crop growth because it restores soil moisture and supplies the water needed for irrigation, both of which have an immediate impact on food supply and security (Minoli *et al.,* 2022). Although the amount of precipitation worldwide may increase overall, it will probably be distributed unevenly, resulting in less precipitation in some places and more intense rainfall in others (Choobeh *et al.,* 2025). Water supplies, agriculture, and ecosystems may be significantly impacted by more frequent and severe weather events like floods and droughts brought on by these patterns of changes (Pepin *et al.,* 2022). Whether encountering increased or decreased rainfall or changes in its spatial and seasonal distribution**,** these shifts impact the distribution of soil moisture, runoff, and groundwater reserves (Patel *et al.,* 2024). Variations in the quantity and timing of rainfall can cause changes in the moisture content of the soil, which can have an immediate impact on plant development and agricultural output. An increase in runoff from areas with more rainfall may result in soil erosion, decreased soil fertility, and the loss of nutrients vital to crop growth (Kipkemoi *et al.,* 2021). Moreover, such changes in rainfall patterns are likely to influence the frequency of floods and droughts, with altered seasonal distribution of precipitation expected to have repercussions on cropping patterns and overall productivity (Oo, 2022). Numerous studies conclude that the impact of global warming is evident across all countries, leading to the conclusion that the effects of global warming are felt in every nation, resulting in diverse environmental, social, and economic transformations (Carleton and Hsiang 2016). Increases in heat wave frequency and intensity, changes in precipitation patterns, and an increase in extreme weather events like hurricanes, floods, and droughts are all consequences of rising global temperatures (Clarke *et al.,* 2022), and these changes impact ecosystems, human health, agriculture, and water supplies globally (Zahoor and Mushtaq 2023). Regarding precipitation, a notable change was observed in several regions including Burkina Faso (De Longueville *et al.,* 2016), Malaysia (Che Ros *et al.,* 2016), Nigeria (Usman *et al.,* 2018), and Ethiopia (Elzopy *et al.,* 2021), where a substantial decrease in total annual rainfall has been recorded. However, rainfall variability show a complicated and uneven distribution over time, indicating that while certain regions experience an upward trend in yearly precipitation, others do not exhibit the same pattern (Syaifullah *et al.,* 2025). This divergence can be attributed to factors such as shifts in monsoon dynamics, regional climate variability, and the broader impacts of global climate change. Consequently, in the broader field of climate studies, understanding rainfall distribution remains crucial, as it directly influences the health of ecosystems, agricultural productivity, and the well-being of human societies (Patel *et al.,* 2024). This study aims to provide readers with a better understanding of how rainfall patterns in this area have changed over time by examining historical rainfall data and identifying trends in these particular districts. The data may clarify regional climate variability and the localized effects of climate change, which are crucial for effectively managing water resources and agricultural planning in these locations. The importance of rainfall in maintaining ecosystems and promoting agricultural practices is increasingly recognized (Tarolli and Straffelini, 2020). Long-term rainfall dynamics in Madurai and Theni districts remain unexplored, creating a significant research gap. The absence of detailed studies on rainfall dynamics in these regions complicates the formulation of comprehensive strategies for sustainable development and climate resilience. While climate studies are expanding globally, Madurai and Theni lack comprehensive rainfall analyses, despite their dependence on seasonal monsoons for irrigation and water supply, making them vulnerable to precipitation variability. The novelty of this study lies in its integrated approach, providing insights into rainfall patterns from 1980 to 2018 through a combination of trend and change-point analyses in these semi-arid settings. The research identifies patterns that support future change prediction and adaptation by combining seasonal, monthly, and annual rainfall assessments. A unique application of multiple statistical methods, including serial correlation diagnostics, ensures finer resolution in variability, emphasizing broader

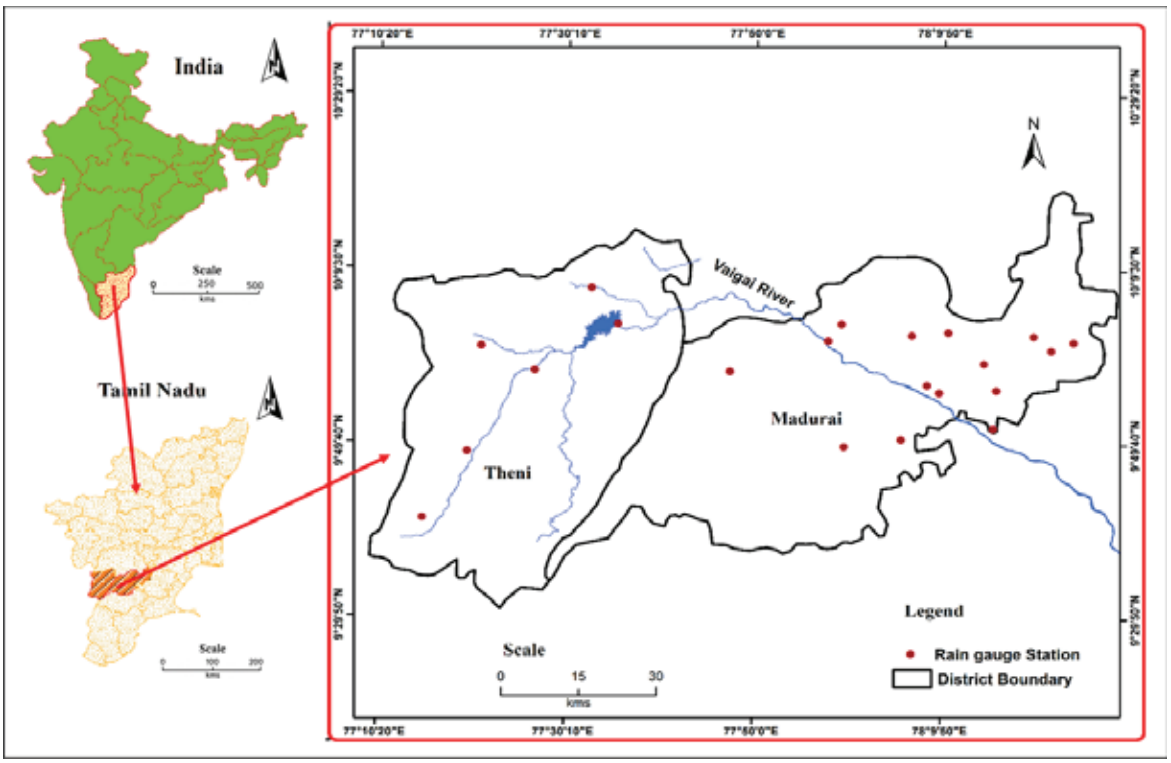

Fig. 1: Geographical location of the study in Theni and Madurai districts in Tamil Nadu, India

climate shifts affecting the region. The objectives are to: i) evaluate long-term rainfall variability over thirty-nine years using daily data from Madurai and Theni, ii) identify seasonal, monthly, and annual trends using robust statistical techniques such as Spearman's Rank Correlation (SRC) and Modified Mann-Kendall Test (MMKT) for significant monotonic trends, iii) detect temporal change-points with methods such as Cumulative Sum Control Chart (CUSUM) and Sequential Mann-Kendall Test (SQMK), and iv) interpret spatial and temporal patterns to support sustainable agricultural planning and climate adaptation. The study was conducted in 2020 at Kalasalingam Academy of Research and Education, and Tamil Nadu Agricultural University, Madurai, India.

MATERIALS AND METHODS

Study area

Theni and Madurai districts in Tamil Nadu, India, were chosen due to their diverse geographical, climatic, and cultural attributes, providing a comprehensive understanding of the factors influencing the ecosystems and communities within the region (Fig. 1). Theni district is a region characterized by hillocks in its northern and southern parts, with the Western Ghats hill range playing a significant role, running parallel from north to south. Smaller hillocks scattered across the district contribute to its distinctive topography. This district has a vast geographical area of 2871.31 square kilometers and is positioned between 9°53' and 10°22' north latitude and 77°17' and 77°45' east longitude (Ponnuchakkammal *et al.,* 2020). Madurai district, situated in the central part of southern Tamil Nadu, shares borders with Dindigul and Tiruchirappalli districts to the north, Sivagangai district to the east, Virudhunagar district to the south, and Theni district to the west, and was selected as a study site due to its strategic location and distinctive features (Fig. 1). Madurai district covers a geographical area of 3741 square kilometers and is located between 9°32' and 10°18' north latitude and 77°00' and 78°30' east longitude. The climate of the combined region is defined by three major rainfall seasons, namely the advance monsoon and Southwest Monsoon (SWM),

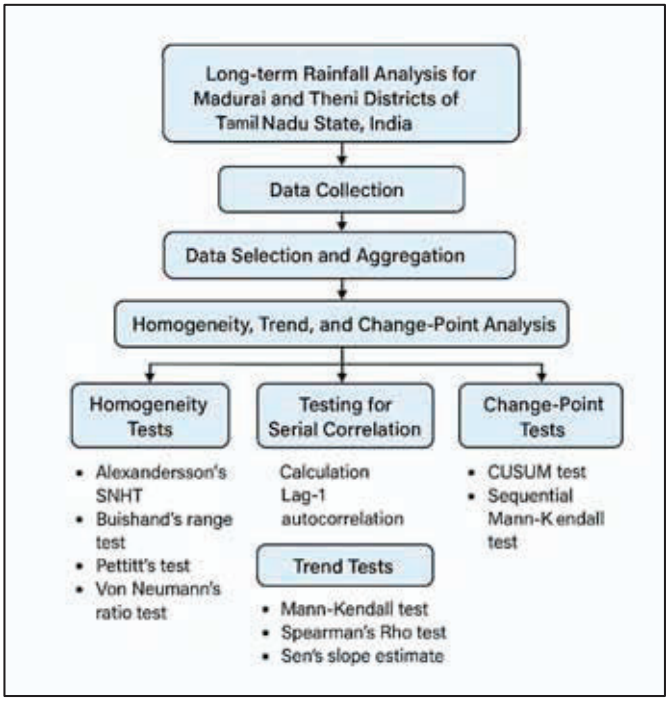

Fig. 2: Methodological framework for long-term rainfall analysis

which occurs from June to September, the Northeast Monsoon (NEM), which occurs from October to December, and the dry season, which extends from January to May. Madurai district experiences intense heat peaking at 42 °C, while Theni, influenced by the Western Ghats, has a more moderate, rainfall-rich climate with cooler hill regions.

Methodology

This study analyzed daily rainfall data from 30 stations in Madurai and Theni districts for the period 1976–2019, sourced from Tamil Nadu government agencies. After quality checks, 21 stations covering 1980–2018 were selected for detailed statistical analysis. Monthly, seasonal, and annual rainfall were derived, followed by homogeneity, trend, and change-point assessments using established tests and specialized R packages. Fig. 2 provides a concise overview of the methodological framework for long-term rainfall analysis in Madurai and Theni districts, Tamil Nadu. Fig. 2 explains the sequential process from data collection and selection to statistical analyses, including homogeneity tests, serial correlation, trend detection, and change-point identification using established methods and tools. Despite the comprehensive approach, several limitations remain. The reduction of stations from 30 to 21 introduces spatial limitations, which may affect the accuracy of local representativeness. The temporal coverage of the study is limited to the period from 1980 to 2018, which may not fully capture longer-term climatic variations and trends**.** The reliance on secondary data may involve inherent inconsistencies. Statistical methods such as the MKT and SRC assume data stationarity, limiting their ability to capture non-linear or abrupt trends. Furthermore, the analysis focuses solely on rainfall, without incorporating other climatic variables such as temperature, humidity, or wind, thereby reducing the broader applicability of the findings for climate adaptation planning in this semi-arid region (Idawati *et al.,* 2024).

Data collection and pre-processing

This study utilized daily rainfall records from 30 rain gauge stations located across the Madurai and Theni districts of Tamil Nadu, sourced from the Department of Economics and Statistics and the Ground Water Division under the Water Resources Department,

Government of Tamil Nadu, covering the period 1976–2019. The datasets underwent rigorous quality control to ensure consistency, completeness, and accuracy before analysis. From the initial 30 stations, 21 were selected based on three key criteria such as data reliability, record completeness, and spatial representativeness. Priority was given to stations with continuous and consistent rainfall records up to 2018 to enhance the reliability of trend analyses. The selected stations ensured balanced spatial coverage, adequately representing both climatic and land-use variations within the study area. Stations with substantial data gaps, inconsistencies, or poor data quality were excluded to minimize analytical bias, thereby providing a robust and credible foundation for assessing long-term rainfall variability and identifying significant regional trends. Despite some limitations, the study offers valuable empirical data that support climate adaptation planning in a semi-arid region, particularly for agriculture and water resource management in Madurai and Theni districts.

Data selection, aggregation, and analytical framework

Following quality screening, daily rainfall datasets underwent rigorous quality control, ensuring consistency, completeness, and accuracy (Purwandani *et al.,* 2025). Out of 30 stations, 21 were selected based on data quality, completeness, and spatial coverage, prioritizing stations with continuous records up to 2018. Stations with gaps, inconsistencies, or questionable data, such as extreme outliers or prolonged missing periods, were excluded to avoid bias and false trend detection. Even though some missing historical data remain, the chosen stations offer a strong foundation for studying long-term changes in rainfall, supporting climate adaptation in the dry areas of Madurai and Theni. Daily rainfall data were aggregated to compute monthly, seasonal, and annual totals. Homogeneity was assessed using Alexandersson's standard normal homogeneity test, Buishand's range test, Pettitt's test, and Von Neumann's ratio test. Serial correlation analysis examined autocorrelation to identify temporal dependencies that could distort trend significance. Trend analysis was conducted using the MMKT, which accounts for autocorrelation. CUSUM and SQMK tests were used to identify temporal shifts in the rainfall data. Homogeneity assessments were supported by AnClim, while R-based tools, including MMKT and trendchange, detected trends and change-points, ensuring robust assessment of long-term rainfall variability.

Treatment of non-homogeneous rainfall data series

In this study, rigorous quality control procedures were applied to the initial dataset of 30 rainfall stations. Homogeneity testing was performed using standardized statistical techniques before trend analysis. Based on these tests, stations identified as having non-homogeneous (doubtful or suspect) rainfall series due to factors like abrupt shifts, data inconsistencies, or extended missing data blocks were systematically excluded from further analysis. Specifically, only 21 stations that met strict criteria of data quality, completeness, and homogeneity were selected for detailed trend assessment. This deliberate exclusion ensured that trend detection was based on high-quality, homogeneous time series, thereby maintaining the integrity and reliability of the analysis. Addressing non-homogeneous data in this way reduces potential biases, allowing the study to produce robust, credible findings on rainfall variability and trends.

Homogeneity, trend, and change-point analysis

A number of statistical tests were utilized to assess homogeneity, trends, and change-points in the rainfall time series. The sequential stages of data analysis are as follows.

Homogeneity tests

The outcomes of homogeneity tests were grouped into three categories: useful when none or only one of the four tests rejected the null hypothesis; doubtful when two tests rejected it; and suspect when three or all four tests rejected it. Two methods were used to assess homogeneity: relative and absolute. Relative methods involved correlating the test data series with a homogeneous series from a neighboring station and were considered more reliable and recommended when suitable reference data were available**.** Absolute methods were preferred when a homogeneous reference series was unavailable or when correlation strength was weak, based on local topographic and climatic data. Relative homogeneity tests used the Anclim software to create a reference series, while absolute tests analyzed individual station

data. After testing, the ratio between the reference series and the observed series was calculated. Four standard statistical tests, including Alexandersson's Standard Normal Homogeneity Test, Buishand's Range Test, Pettitt's Test, and Von Neumann's Ratio Test, were applied to evaluate homogeneity.

Alexandersson's standard normal homogeneity test

The standard normal homogeneity test is used to detect inhomogeneities or abrupt changes in the mean of a climatic time series by evaluating the deviation of sub-period means from the overall mean. The standard normal homogeneity test statistic is calculated using Equation (Eq.) 1 (Kumar and Thangavel, 2025):

$$T(k) = k\bar{z}_1^2 + (n-k)\bar{z}_2^2 \text{ for } k = 1, 2, \ldots, n \quad (1)$$

Where: $T(k)$ represents the test value calculated at each potential change point k within a time series of n total observations. The terms $\bar{z}_1^2$ and $\bar{z}_2^2$ are the average standardized anomalies (z-scores) before and after the point k, respectively. The factor k weights the squared standardized average of the first segment, while ($n - k$) weights the squared standardized average of the second segment. This formulation helps to assess how much the data before and after k deviates from the overall mean and the value of $T(k)$ across all k indicates the most likely location of an inhomogeneity or sudden shift in the time series. Eq. 2 defines how to calculate standardized mean values before and after a potential change point in the standard normal homogeneity test (Kumar and Thangavel, 2025):

$$\bar{z}_1 = \frac{1}{k}\sum_{i=1}^{k}\frac{(X_i - \bar{X})}{s} \text{ and}$$

$$\bar{z}_2 = \frac{1}{(n-k)}\sum_{i=k+1}^{n}\frac{(X_i - \bar{X})}{s} \quad (2)$$

Where: n this equation, X_i is the observed value at time i, $\bar{X}$ is the overall mean of all observations from $i = 1$ to n, and s is the standard deviation of the full dataset. These formulas convert the data into standardized form (z-scores) by removing the overall mean and scaling by standard deviation, then compute the average standardized deviation for the two segments, before and after k. These standardized averages are critical for the standard normal homogeneity test as they allow for the detection of shifts in mean values while accounting for natural variability in the data.

Buishand's range test

Buishand's range test is used to identify inhomogeneities or sudden shifts in the mean of a climatic time series by assessing cumulative deviations of data points from the overall mean. The Buishand range statistic is calculated using Eq. 3 (Gadedjisso-Tossou *et al.,* 2021; Anusty *et al.,* 2023):

$$S_0^* = 0 \text{ and } S_k^* = \sum_{i=1}^{k}(X_i - \bar{X}) \text{ where } k = 1, 2, \ldots, n \quad (3)$$

Where: X_i is the observed value at time i, $\bar{X}$ is the overall mean of all n observations, and S_k^* represents the cumulative sum of deviations from the mean up to time step k. This formulation constructs a running total of how each value deviates fro m the mean, beginning with S_0^*. If the time series is homogeneous, the cumulative deviations fluctuate randomly around zero; however, a significant shift in the mean will cause a systematic trend or drift in the S_k^* values. The range (i.e., the difference between the mínimum and maximum S_k^*) is then analyzed to identify the presence and position of a potential inhomogeneity in the dataset.

Pettitt's test

Pettitt's test is a non-parametric method commonly used to detect a single abrupt change point in the central tendency (median) of a climatic time series without requiring assumptions of normality. The test statistic is derived from integer-based calculations and is computed using Eq. 4 (Gadedjisso-Tossou *et al.,* 2021; Anusty *et al.,* 2023):

$$Y_k = 2\sum_{i=1}^{k} r_i - k(n+1) \text{ where } k = 1, 2, \ldots, n \quad (4)$$

Where: Y_k denotes the test statistic at each point k, r_i represents the ith observation when all n values in the time series are ranked in ascending order, and k is the index representing a potential change point. The formula calculates the cumulative

sum of ranks up to k, adjusted by $k(n+1)$, to measure the shift in the distribution before and after k. A significant change point is identified where the absolute value of Y_k is maximized, indicating a probable point of inhomogeneity or regime shift within the dataset.

Von Neumann's ratio test

Von Neumann's ratio test is a statistical method applied to detect randomness or the presence of systematic shifts (inhomogeneities) in the mean of a climatic time series by evaluating the smoothness or variability between successive observations. The test statistic is calculated using Eq. 5 (Gadedjisso-Tossou *et al.,* 2021):

$$N = \sum_{i=1}^{n-1}\left(X_i - X_{i+1}\right)^2 \Big/ \sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2 \quad (5)$$

Where: N represents the Von Neumann ratio, X_i and X_{i+1} are consecutive observed values in the time series, $\bar{X}$ is the overall mean of the n observations, and the summations extend over the entire dataset. The numerator quantifies the squared differences between consecutive data points, while the denominator captures the total variance of the time series. In a homogeneous time series, the ratio N tends to be close to 2.0; significant deviations from this value indicate potential inhomogeneities or non-random structures such as abrupt changes or trends within the dataset.

Testing for serial correlation

Testing for serial correlation is employed to assess the presence of autocorrelation or persistence within a climatic time series, which can indicate dependencies between successive observations and affect the validity of trend analysis. Lag-k serial correlation coefficients are generally computed to examine correlations at various time lags, with particular emphasis on the Lag-1 serial correlation coefficient (ρ_1), which is frequently used due to its simplicity and relevance (Basistha *et al.,* 2009). The Lag-1 serial correlation coefficient is calculated using Eq. 6 (Malik and Kumar, 2020):

$$\rho_1 = \frac{\frac{1}{n-1}\sum_{i=1}^{n-1}(x_i - E(x_i)).(x_{i+1} - E(x_i))}{\frac{1}{n}\sum_{i=1}^{n}(x_i - E(x_i))^2} \quad (6)$$

Where: X_i and X_{i+1} are consecutive observed values in the time series of length n, and $E(x_i)$ represents the mean of the entire series. The numerator computes the average product of deviations between adjacent observations, while the denominator represents the variance of the time series. A significant value of $\tilde{n}_1$ indicates positive or negative correlation between successive observations, highlighting the presence of serial dependence or memory within the dataset, which is crucial for accurately interpreting trend results and adjusting statistical analyses accordingly.

Trend tests

MKT is widely used to detect monotonic trends in climatic time series, especially when data are serially independent. When serial correlation is absent, MKT and Spearman's Rho are applied for trend detection, while Sen's Slope (SS) estimates the trend magnitude. The MKT statistic S is calculated using Eq. 7 (Vani *et al.,* 2023; Mukherjee *et al.,* 2025):

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sign\left(x_j - x_i\right) \quad (7)$$

Where: X_i and X_j are observed data points, and n is the total number of observations. The sign function counts positive or negative differences, with the cumulative S value indicating the direction and presence of a trend.

Change-point tests

The analysis included the utilization of the distribution-free CUSUM test to examine variations in mean values within the time series. Additionally, the SQMK test was employed to identify sequential step changes in the time series (Vani *et al.,* 2023). For statistical analysis, the MMKT and trendchange R library packages were utilized. The MMKT package facilitated non-parametric tests, such as the MKT and SRCC tests, including MMKTs. The trendchange package was utilized for analyzing change points. Both packages are available through the Comprehensive R Archive Network (CRAN) repository and GitHub, providing free access to package functionalities.

RESULTS AND DISCUSSIONS

This study comprehensively evaluates long-term

rainfall variability in Madurai and Theni districts, focusing on data homogeneity, serial correlation, and temporal trends. Rainfall series were classified as useful, doubtful, or suspect using four established homogeneity tests, applied through both relative and absolute approaches. Understanding rainfall dynamics and data dependencies was made possible by serial correlation analysis. Trend analysis across monthly, seasonal, and annual scales revealed variations in rainfall patterns across the stations. Change-point detection through CUSUM and SQMK tests identified key temporal shifts, including an early deviation at Gudalore during the NEM in 1986. Time-series plots further illustrated distinct patterns in rainfall behaviour, supporting the identification of localized climatic influences.

Homogeneity of rainfall data

The classification of the rainfall series into doubtful, suspect, or useful categories was based on the outcomes of the four homogeneity tests. Most of the months were classified as suspect in the relative and absolute homogeneity tests (Table 1). Absolute homogeneity testing identified 23 doubtful, 33 suspect, and the remainder as useful series. Annual rainfall was suspect at eight stations, with Edayappatti, Melur, and Thallakulam classified as doubtful. Most stations showed suspect classifications for SWM rainfall, except Uthamapalayam, which exhibited acceptable data quality during the period of analysis. NEM rainfall was doubtful at Tanyamangalam and Bodi, and suspect at Edayappatti, Madurai South, and Usilampatti. Summer rainfall was predominantly doubtful. This detailed assessment ensures accurate characterization of rainfall variability, enhancing understanding of climate impacts and supporting water resource planning in Tamil Nadu.

Treatment of non-homogeneous series in trend and change-point analyses

Adjustment and data selection procedures in this study were guided by standard climatological practices, emphasizing data quality and representativeness. A combination of exclusion and selective retention strategies was applied to balance analytical robustness with spatial coverage across Madurai and Theni districts.

i. Adjustment using standard climatological methods: Rainfall data were subjected to thorough quality control and homogeneity testing (Table 1), categorizing series as suspect or doubtful. The lack of confirmed homogeneous reference stations in the districts of Madurai and Theni prevented any statistical adjustments even though 23 dubious and 33 suspicious series were found. This approach prevented potential artificial trends from ratio-based corrections.

ii. Exclusion from analysis: Out of 30 rainfall stations, 21 were selected for detailed analysis, excluding those with major data gaps or classified as highly doubtful based on homogeneity results (Table 1). This ensured the core analysis relied on stable, representative datasets, enhancing reliability in trend detection.

iii. Retention of unadjusted series: For seasonal datasets (SWM, NEM, summer), certain suspect or doubtful series were retained unadjusted to maintain spatial coverage. The use of non-parametric methods minimized the impact of moderate inhomogeneities. Emphasis was placed on establishing relative patterns across time rather than precise climatological averages to reflect relevant long-term fluctuations.

Analysis of serial correlation

Significant insights into the temporal dynamics of rainfall in Madurai and Theni districts can be gained from the analysis of serial correlation in long-term rainfall data. The serial correlation tests showed that among the 357 rainfall series analyzed, 17 exhibited serial correlation at the 90 Percent (%) confidence interval (Table 2). Annual rainfall exhibited autocorrelation at Tirumangalam, Usilampatti, Gudalore, and Periyakulam. Winter rainfall showed autocorrelation at Tirumangalam, and summer rainfall at Cholavandan. SWM rainfall showed no autocorrelation at any station, while NEM rainfall exhibited autocorrelation at Edayapatti and Usilampatti. Monthly autocorrelation appeared at Tirumangalam (February, July, December), Periyakulam (January), Usilampatti and Bodi (November), Uthamapalayam and Veerapandi (May), and Madurai South (June). From Table 2, it is evident that a clear temporal connection exists, and rainfall in Madurai and Theni is not fully random due to considerable serial correlation. The presence of strong serial correlation indicates rainfall patterns exhibit some level of predictability, supporting agricultural planning and water resource management.

Table 1: Summary of homogeneity results

Name of stations	Absolute homogeneity		Relative homogeneity	
	Doubtful	Suspect	Doubtful	Suspect
Airport_Madurai	None	September	None	None
Andipatti	Summer	Annual	October, NEM	Annual
Chittampatti	May	None	September	None
Edayapatti	Annual, Summer	May, NEM	May, September, SWM	November, December, Annual, Summer, NEM
Kallanthiri	None	None	None	None
Melur	Annual	September, SWM	Annual, NEM	October
Mettupatti	None	None	None	None
Pulipatti	June, August	May	NEM	Annual
Madurai_South	September	Annual, NEM	January, October, November	Annual, NEM
Sholavandan	None	September SWM	February	September, SWM
Tanyamangalam	NEM	May August	May, Annual, SWM	January
Thallakulam	Annual	None	November	None
Tirumangalam	February, October	Winter	February, Winter	Summer
Tiruppuvanam	May	August, Annual, Summer, SWM	September, December	Annual, SWM, NEM
Usilampatti	None	September, November Annual, SWM, NEM	August	September, October, November, December, Annual, SWM, NEM
Bodi	April, NEM	August, Annual	Summer, SWM	August Annual
Gudalore	None	None	May, Summer	None
Periyakulam	None	Annual	None	None
Uthamapalayam	Summer, SWM	May, August, Annual	NEM	Annual
Vaigai Dam	May, August	None	February, October NEM	None
Veerapandi	April, June July, Summer	May, August, Annual, SWM	August, Summer	September, October, Annual, SWM

Analysis of trends in rainfall

From Table 2, monthly, annual, and seasonal trend analysis revealed key patterns. January and March showed no significant changes, while February had a negative trend at Tirumangalam. Positive trends appeared in April (Edayapatti, Bodi, Veerapandi) and June (Pulipatti, Bodi, Veerapandi). July and August showed strong increases, especially at Veerapandi (1% level), while September had widespread decreases. October increased at Andipatti, while Usilampatti

Table 2: Outcomes of the MK test, SS test, and SRC Coefficient (SRCC) test derived without taking into account the impact of serial correlation

Station name	Annual			Winter			Summer			South-West monsoon			North-East monsoon		
	MK	SS	SRCC	MK	SS	SRCC	MK	SS	SRCC	MK	SS	SRCC	MK	SS	SRCC
Airport_Madurai	−1.31	−3.52	−1.22	0.60	0.01	0.61	0.65	0.67	0.55	−1.16	−1.39	−1.22	−0.54	−1.23	−0.47
Andipatti	2.18	7.35	2.09	−0.23	0.00	−0.20	2.24	2.17	2.15	0.54	0.89	0.47	1.40	3.49	1.50
Chittampatti	0.82	2.99	0.80	0.03	0.00	0.08	1.32	1.79	1.49	0.34	0.45	0.52	0.60	0.96	0.56
Edayapatti	2.44	5.83	2.63	0.45	0.00	0.44	2.23	1.87	2.35	1.39	2.00	1.54	1.65	2.47	1.93
Kallanthiri	0.19	1.09	0.04	−0.18	0.00	−0.13	1.37	1.23	1.27	−0.22	−0.61	−0.23	0.15	0.33	0.07
Melur	−1.14	−3.58	−1.46	−0.01	0.00	−0.07	0.29	0.42	0.22	−2.20	−2.73	−2.43	−0.58	−1.34	−0.58
Mettupatti	1.02	4.29	0.84	0.57	0.00	0.65	1.78	1.76	1.71	−0.24	−0.55	−0.27	0.68	1.57	0.76
Pulipatti	0.05	0.22	0.12	0.55	0.00	0.64	1.66	1.43	1.65	−0.01	−0.05	0.23	−0.12	−0.24	−0.15
Madurai_South	−1.33	−4.47	−1.50	−0.64	0.00	−0.58	0.06	0.14	−0.04	−1.06	−1.68	−0.94	−1.33	−3.05	−1.30
Sholavandan	−1.33	−5.23	−1.31	−0.57	0.00	−0.57	0.52	0.67	0.49	−1.92	−3.27	−2.09	−0.27	−0.75	−0.47
Tanyamangalam	0.85	3.33	0.92	0.06	0.00	0.21	1.81	1.63	1.88	1.19	1.70	1.28	0.05	0.15	0.18
Thallakulam	0.02	0.19	−0.19	0.37	0.00	0.35	0.99	0.80	1.00	−0.19	−0.36	−0.27	−0.28	−0.64	−0.35
Tirumangalam	−0.12	0.00	−0.25	−0.85	−0.13	−1.03	−1.46	−2.12	−1.39	0.97	1.44	0.81	0.34	1.06	0.45
Tiruppuvanam	3.22	13.79	3.17	0.50	0.00	0.48	2.40	2.99	2.49	2.20	5.89	2.33	1.65	4.24	1.70
Usilampatti	−2.66	−13.40	−2.82	−0.63	0.00	−0.21	0.12	0.27	−0.02	−2.98	−4.73	−3.13	−2.61	−9.27	−2.36
Bodi	2.47	7.96	2.49	−0.53	−0.05	−0.38	1.86	2.27	2.03	1.98	2.00	2.01	1.60	2.82	1.80
Gudalore	1.04	4.28	1.01	0.00	0.00	0.22	−0.40	−0.40	−0.38	0.58	1.50	0.58	1.69	3.12	1.74
Periyakulam	1.81	7.01	1.88	0.23	0.00	0.36	0.68	0.79	0.70	1.40	2.11	1.31	0.90	2.29	1.07
Uthamapalayam	2.30	9.55	2.18	0.84	0.10	1.13	1.96	2.93	1.84	1.94	2.93	2.00	1.45	3.30	1.30
Vaigai Dam	0.19	0.58	0.25	1.07	0.13	1.12	1.11	1.21	1.11	−0.39	−0.42	−0.43	−0.36	−0.81	−0.57
Veerapandi	3.51	13.22	3.29	−0.15	0.00	0.01	3.47	4.13	3.34	3.47	4.88	3.12	1.21	2.68	1.37

significant trend at 10% confidence level

significant trend at 5% confidence level

significant trend at 1% confidence level

Table 3: Outcomes of MMKT, specifically applied to serially correlated data

Station name	Time series	PW	TFPW	BCPW	MMKH	MMKY
Edayapatti	NEM	1.03	1.63	1.01	1.81*	3.05***
Pulipatti	June	0.77	1.66*	0.54	1.82*	4.20***
Sholavandan	Summer	1.13	0.80	1.13	0.52	1.63
Tirumangalam	February	−1.68*	−1.68*	−1.68*	−1.19	−1.29
Tirumangalam	July	0.23	0.23	0.23	0.00	0.00
Tirumangalam	December	0.00	0.126	−0.04	−0.65	−1.21
Tirumangalam	Annual	0.12	0.15	0.14	−0.11	−0.46
Tirumangalam	Winter	−1.58	−2.11**	−1.58	−1.13	−0.73
Usilampatti	November	−1.48	0.80	0.56	0.00	1.02
Usilampatti	Annual	−1.76*	0.15	0.14	−0.11	−0.45
Usilampatti	NEM	−2.26**	1.08	0.74	0.34	0.67
Bodi	November	0.85	1.15	0.55	1.00	1.96
Gudalore	Annual	0.45	1.15	0.72	1.19	1.36
Periyakulam	January	−0.41	−0.41	−0.51	−0.63	−0.68
Periyakulam	Annual	1.25	1.98**	1.28	1.81*	2.31**
Uthamapalayam	May	0.00	0.17	0.02	0.69	0.78
Veerapandi	May	1.46	2.64***	1.66*	3.36***	4.13***

*significant at the confidence level of 10%; **significant at the confidence level of 5%; ***significant at the confidence level of 1%.

declined in November and December. Strong annual increases were observed in Tiruppuvanam and Veerapandi (1%), while Andipatti, Edayapatti, Bodi, Uthamapalayam (5%), and Periyakulam (10%) showed moderate increases, whereas Usilampatti exhibited a sharp annual decrease of 1%. Winter trends were insignificant, while summer increased at most stations except Tirumangalam and Gudalore. SWM rainfall at Veerapandi showed a highly significant upward trend at 1% confidence (MK=+3.51, SS=+13.22; summer MK=+3.47, SWM MK=+3.47). For NEM, Edayapatti, Thiruppuvanam, and Gudalore exhibited significant upward trends, while Usilampatti showed significant downward trends at 1% confidence (annual MK=−2.66, SS=−13.40; SWM MK=−2.98; NEM MK=−2.61). Tiruppuvanam also showed positive trends annually (MK=+3.22, SS=+13.79), in summer (MK=+2.40), and SWM (MK=+2.20). Edayapatti had a positive annual trend (MK=+2.44, SS=+5.83). Airport_ Madurai and Melur showed weak or non-significant trends. MMKTs (Table 3) indicate increasing trends at Edayapatti (NEM), Pulipatti (June), Periyakulam (Annual), and Veerapandi (May). From Table 3, it may be noted that rainfall trends exhibit substantial spatial and temporal variability, effectively captured through MMKT, namely Pre-Whitening (PW), Trend-Free Pre-Whitening (TFPW), Bias-Corrected Pre-Whitening (BCPW), MMK with Hamed and Rao Variance Correction (MMKH), and MMK with Yue and Wang Correction (MMKY), all specifically designed to address serial correlation. The novelty of this analysis lies the application of advanced techniques, such as MMKY and MMKH, for high-resolution trend detection. Strong positive trends were observed at Veerapandi (May, +4.13, $p<0.01$), Pulipatti (June, +4.20, $p<0.01$), and Edayapatti (NEM, +3.05, $p<0.01$). Periyakulam exhibited an annual increase (+2.31, $p<0.05$) only after correction, revealing previously hidden trends. Negative trends at Tirumangalam (February) and Usilampatti (Annual, NEM) lose significance after correction, showing the impact of serial correlation. These findings confirm the importance of corrected methods for precise rainfall trend analysis.

Fig. 3 shows SQMK plots capturing prograde and retrograde interactions to identify rainfall change points and trend shifts. A significant summer change point (1999) appeared at Bodi (95% confidence). Veerapandi and Tiruppuvanam exhibit steady increases in SWM and annual increases with strong prograde values (+3.5 and +3.2), aligning with both MK and MMKY trends. Usilampatti displays early declines that stabilize after 2000, with annual and NEM prograde values below −2.6. SQMK adds value by revealing the timing and direction of rainfall shifts, offering dynamic insights into rainfall variability. Fig. 3 presents the SQMT results with prograde u(t) and retrograde u'(t) series plotted against the 95% confidence limits (±1.96). By standard SQMK interpretation, a statistically significant change

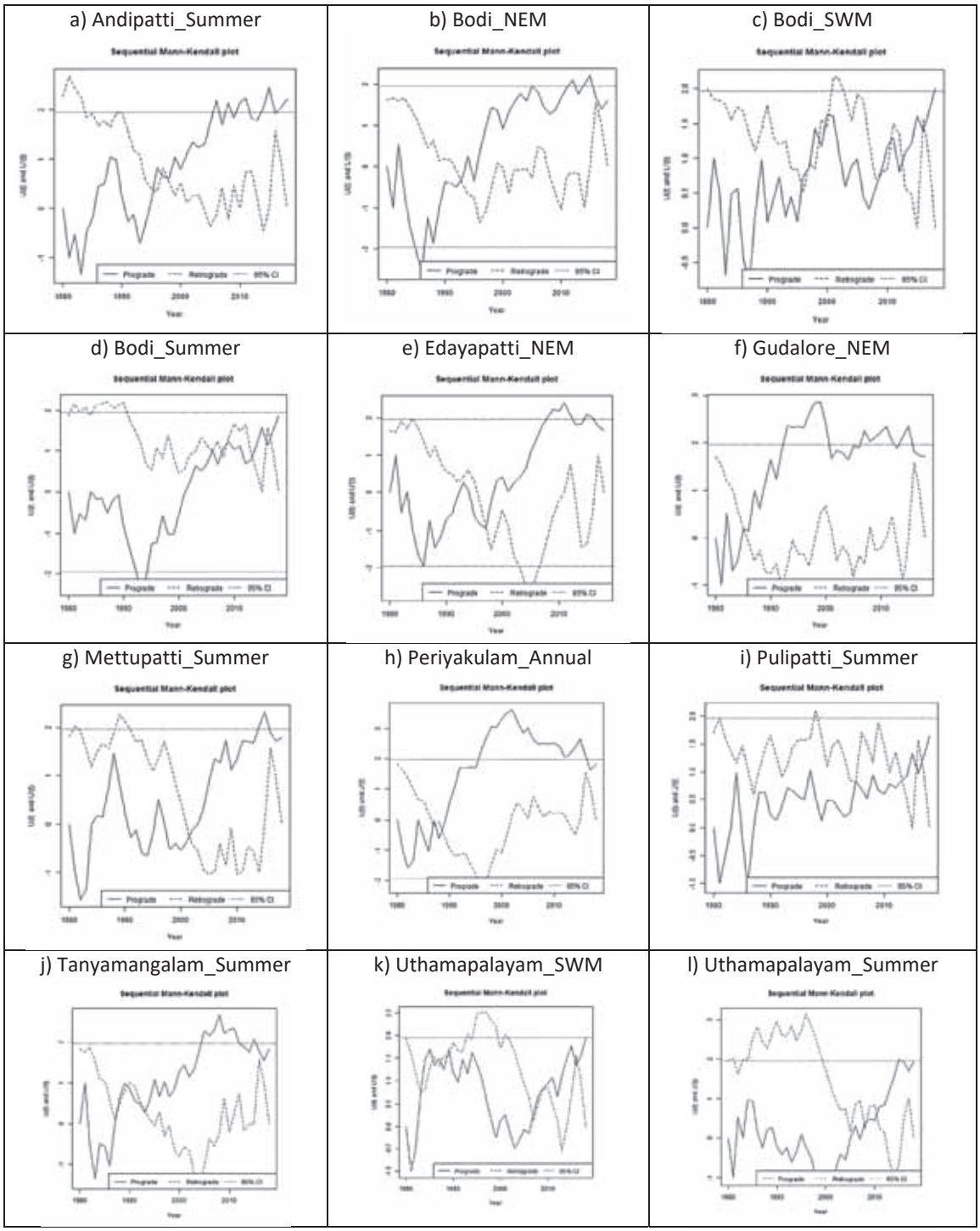

Fig. 3: SQMK test output showing the interaction between prograde and retrograde series

Table 4: Summary of the change in trends

Stations	Series	CUSUM	SQMK
Andipatti	Summer	1994*	1995
Mettupatti	Summer	2001	2002
Pulipatti	Summer	2010	2014
Tanyamangalam	Summer	1993	1994
Bodi	Summer	1999**	2006
Bodi	SWM	2003	1996
Bodi	NEM	1993	1993
Gudalore	NEM	1986	1986
Uthamapalayam	Summer	2001	2008
Uthamapalayam	SWM	2003**	2007
Veerapandi	Summer	1998**	1995
Edayapatti	NEM	1997*	1998
Periyakulam	Annual	1995**	1987

*significant at the confidence level of 10%; **significant at the confidence level of 5%

point occurs when u(t) and u'(t) intersect and diverge beyond ±1.96. In this analysis, intersections between u(t) and u'(t) are observed but do not diverge beyond ±1.96 after corssing, indicating the absence of statistically significant change points. Confidence limit lines verify that junctions are not significant and help with the visual evaluation of trend shifts. This temporal detail supports practical insights for planning and agriculture by assisting in the identification of trends, their timing, and their persistence. Additionally, Fig. 3 includes time-series graphs depicting environmental parameters from multiple locations, highlighting diverse local patterns. Andipatti, Bodi, and Tanyamangalam (Summer) show mid-summer peaks from +5 to +8. Bodi (NEM) displays sharp spikes between −6 and +6. Edayapatti (NEM) shows a steady upward trend exceeding +2.5. Gudalore (NEM) follows a sawtooth pattern between +2 and −2. Mettupatti and Uthamapalayam (Summer) exhibit rises peaking at +4 and declines to −3. Periyakulam (Annual) cycles between +3 and −2. Pulipatti (Summer) plateaus after increases up to +3. Uthamapalayam (SWM) shows irregular fluctuations between +4 and −4. These patterns indicate diverse temporal behaviours across locations, reflecting distinct environmental dynamics and variability.

The trend directions and significance levels reported in Tables 1 and 2 have been directly cross-referenced with the temporal evolution patterns illustrated in Fig. 3 to ensure analytical consistency. Stations such as Veerapandi and Tiruppuvanam, which show statistically significant increasing trends in annual and SWM rainfall as indicated by positive slope values and high significance levels in Tables 1 and 2, show persistent upward trajectories in Fig. 3. Conversely, the statistically significant long-term decreasing trends observed at Usilampatti are corroborated by the sustained downward progression in the SQMK curves in Fig. 3. The interpretation of Fig. 3 has been systematically aligned with the statistical outcomes by associating graphical features, such as abrupt shifts, stabilization phases, and trend reversals, to corresponding change-points and slope estimates in Tables 1 and 2. This integrative approach provides a coherent narrative that combines statistical significance and temporal dynamics, enhancing the accuracy of trend detection and minimizing interpretative bias. The consistency between Tables 1 and 2 with Fig. 3 offers a more comprehensive understanding of regional rainfall variability, strengthening the study's relevance for climate trend assessment and practical applications in water resource management and agricultural planning. These quantified patterns guide region-specific climate adaptation, such as improved water storage where rainfall declines and optimized cropping where it increases. The alignment of statistical results with rainfall behaviour ensures data-driven, reliable adaptation planning, offering practical guidance for policymakers and resource managers. Table 4 presents significant changes in rainfall trends across stations and seasons, identified through CUSUM and SQMK tests. From Table 4, it may be observed that Gudalore exhibited changes during the NEM in 1986, indicating the earliest observed shift. Periyakulam showed an annual rainfall trend change in 1987, with SQMK indicating earlier stabilization than CUSUM. Edayapatti recorded NEM shifts in 1997 and

1998, showing gradual adjustments. Variability was demonstrated by variations in summer rainfall in Tanyamangalam in 1993 and 1994 and Andipatti in 1994 and 1995. Veerapandi showed summer changes in 1995 and 1998, while Bodi recorded significant shifts, including NEM in 1993, SWM in 1996 and 2003, and summer in 1999 and 2006, reflecting rainfall complexity. Similarly, Uthamapalayam exhibited SWM trends in 2003 and 2007, along with summer shifts in 2001 and 2008. Mettupatti showed summer shifts in 2001 and 2002, stabilizing over time, whereas Pulipatti exhibited changes more recently, in 2010 and 2014. These results highlight spatial and temporal rainfall variability, underscoring the need for location-specific climate strategies.

Rainfall trends from 1980–2018 across Madurai and Theni show clear regional patterns by geography and season. Western hilly regions (Bodi, Uthamapalayam, Andipatti) show moderate increases in annual and seasonal rainfall, while eastern plains (Veerapandi, Tiruppuvanam, Edayapatti) have stronger, statistically significant increases, especially during the SWM. Central and rain-shadow areas (Usilampatti, Tirumangalam) show pronounced declining trends annually and during NEM. The SWM shows the most consistent positive trends, while NEM declines are primarily localized to Madurai's interior. Change-points cluster in the 1980s–1990s for northern/eastern stations and post-2000s for southern/western areas, confirming asynchronous shifts and the importance of localized adaptation. Patel *et al.* (2024) found significant rainfall trends at 95% confidence, with no winter changes but increases at 88% of grid points (1960–2000), especially in monsoon and summer over 76% of eastern India's river basins. Muthumurugan *et al.* (2021) identified shifts in 1995, 2000, and 2003 (5% level), linking rainfall variability to uneven agricultural growth in Tamil Nadu. Muthiah *et al.* (2024) reported sharp rainfall shifts in the Vaippar Basin (1995, 2001, 2003, 5% level), with rising summer and monsoon variability. Oo (2022) observed interannual variability in Upper Myanmar, especially during El Niño Southern Oscillation (ENSO) years 1997 and 2002 (10% level), affecting winter rainfall. Collectively, these studies emphasize the necessity for focused, site-specific adaptation measures by highlighting increasing rainfall variability and changing seasonal patterns. From Table 4, important rainfall shifts occurred at Gudalore (1986, NEM), Periyakulam (1987, Annual), Edayapatti (1997–1998, NEM), and Pulipatti (2010, 2014, June), mostly between 1993–2003, with recent shifts post-2010. This indicates increasing rainfall instability, underscoring the need for adaptive strategies to safeguard water resources, agriculture, and regional livelihoods.

Regional pattern extraction based on study results

The rainfall data underwent rigorous quality assessment and homogeneity testing, with outcomes summarized in Table 1. Stations were categorized as suspect or doubtful based on the standard climatological tests applied. Following these assessments, 21 stations with acceptable data quality were retained, ensuring consistency and representativeness for further analysis.

i. Data quality assessment and station selection: Rainfall data underwent rigorous quality control and homogeneity testing, with results summarized in Table 1. Stations were classified as suspect or doubtful based on outcomes from Alexandersson's SNHT, Buishand's test, Pettitt's test, and Von Neumann's ratio. Based on these classifications and record continuity, 21 stations were selected for further analysis. The spatial distribution of selected stations is shown in Fig. 1, which groups them into three physiographic zones: i) western hilly (e.g., Andipatti, Bodi), ii) central transitional (e.g., Edayapatti), and iii) eastern plains (e.g., Usilampatti, Tiruppuvanam). This zoning framework supports regional pattern analysis by accounting for topographic and climatic gradients.

ii. Rainfall characteristics and spatial variability: Monthly, seasonal, and annual rainfall totals were derived from the cleaned daily data series. Table 2 shows the mean, standard deviation, and Coefficient of Variation (CV). Western hilly stations recorded higher mean rainfall with lower CVs, indicating more stable precipitation patterns, while eastern plains showed higher CVs and irregular seasonal patterns, indicating greater climatic variability and vulnerability.

iii. Temporal trends in rainfall: Rainfall trends were analyzed using the MMK and SQMK tests, results of which are summarized in Table 3. Strong increasing trends were found in Veerapandi (Annual MK=+3.51, SWM MK=+3.47) and Edayapatti (Annual MK=+2.44), both situated in the western and central zones. Conversely, Usilampatti (Annual

MK=−2.66, NEM MK=−2.98) displayed significant decreasing trends, especially in the NEM season. Fig. 2 outlines the methodological workflow, detailing sequential steps including homogeneity checks, serial correlation correction, trend analysis, and change-point detection, ensuring analytical robustness.

iv. Seasonal trends and intra-annual variability: Further disaggregation of seasonal rainfall trends is shown in Table 4. Positive summer trends appeared in western hilly stations like Andipatti (MK +2.51) and Bodi (MK +2.37), while winter showed no significant trends. NEM declines were concentrated in eastern stations, with Usilampatti (MK −2.61, SS −9.27) showing the sharpest decrease. This highlights spatial climate disparities and the need for region-specific adaptation needs.

v. Change-point detection and temporal shifts: Change-point detection using SQMK analysis is illustrated in Fig. 3. Veerapandi and Tiruppuvanam showed upward trend shifts around 2003, indicating recent rainfall intensification, while Usilampatti experienced a downward shift around 1995, aligning with declining NEM trends. These breakpoints reflect long-term climatic transitions influenced by broader climate drives.

vi. Synthesis of regional rainfall patterns and implications: The combined interpretation of Tables 1–4 and Figs. 1–3 reveals distinct regional rainfall patterns across Madurai and Theni districts. Western hills show increasing and more stable rainfall trends, while eastern plains exhibit declines during key monsoon periods**.** These patterns underscore the importance of targeted adaptation strategies for agriculture, water management, and policy development in this semi-arid region.

Comparison with previous studies

This study provides novel localized rainfall trend analysis for Madurai and Theni, using advanced statistical methods like homogeneity testing, change point detection, and serial correlation adjustment. It offers high-resolution station-level insights, improving understanding of spatial-temporal variability and aiding targeted adaptation. The inclusión of serial correlation assessment ensures accurate trend interpretation by capturing temporal dependencies.

Serial correlation (90% confidence)

At 90% confidence level, the present study detected significant serial correlation in 17 out of 357 rainfall series, including annual rainfall at Tirumangalam, Usilampatti, Gudalore, and Periyakulam. Seasonally, serial correlation was absent in SWM but observed in NEM at various stations. These results align with Patakamuri *et al.* (2020), who reported increasing summer rainfall, highlighting temporal rainfall relationships. Similarly, Giri *et al.* (2023) observed contrasting monthly trends, with increases in August and declines in September. Building on these findings, the key novelty of this study is the identification of serial correlation patterns across annual, seasonal, and monthly scales with station-specific details, thereby advancing the understanding of local rainfall dynamics.

Annual rainfall trends

The present study identified increasing annual rainfall trends at eastern and western boundary stations such as Veerapandi (+8.56 millimeters/year (mm/year)), Periyakulam (+7.45 mm/year), and Pulipatti (+6.97 mm/year). Simultaneously, decreasing trends were recorded at interior stations like Usilampatti (−6.74 mm/year), Gudalore (−6.20 mm/year), and Tirumangalam (−5.89 mm/year). Sekar *et al.* (2025) reported overall stable annual rainfall, contrasting with the spatial divergence identified in the present study. Mohan Kumar *et al.* (2022) observed rising trends in plains and coastal areas with annual means ranging from 718.4 to 2268.6 mm per year, supporting increases in the eastern plains of the present study. This analysis gives fine-scale trends at the station level and identifies clear reductions in interior regions such as Madurai, which earlier studies did not capture, offering valuable insights for regional water management (Rangarajan *et al.,* 2019).

SWM and NEM trends

The present study showed substantial SWM rainfall increases at Veerapandi (+9.35 mm/year), Pulipatti (+8.70 mm/year), Periyakulam (+7.78 mm/year), and Bodi (+7.17 mm/year), while NEM rainfall declined at Usilampatti (−8.14 mm/year), Tirumangalam (−7.45 mm/year), and Gudalore (−6.82 mm/year), but increased at Veerapandi (+7.67 mm/year) and Periyakulam (+6.84 mm/year). The present study's findings of increasing SWM and declining NEM rainfall with notable spatial variability align with Rangarajan *et al.* (2019), Singh *et al.* (2021a), Mohan

Kumar *et al.* (2022), and Sharma *et al.* (2024), who reported significant seasonal shifts across Tamil Nadu and adjoining regions. Declining SWM in Madurai, as observed by Sanjeevaiah *et al.* (2021), raises agricultural concerns, while slight NEM increases in certain pockets fail to compensate for inter-seasonal instability. Consistent with Jones *et al.* (2022), emerging signs of rainfall stabilization suggest evolving climatic influences, potentially linked to land use changes or ENSO. This highlights the importance of localized, season-specific assessments to understand rainfall variability in Tamil Nadu.

Change points (years)

The present study identified several notable change points, including the 1999 summer shift at Bodi, the 1986 annual shift at Gudalore, and the 2014 shift at Pulipatti, along with multiple shifts across seasons and stations. Pawar *et al.* (2023) identified annual and seasonal change points in the Mahi Basin using MK and Innovative Trend Analysis (ITA) tests, which alligns with the multi-temporal change points detected in the present study. Similarly, Mishra (2020) linked major droughts in 1899, 1876, 2000, 1918, and 1965 to ENSO events, indicating broader climatic drivers potentially influencing change points around 2000 observed in this analysis. Rao *et al.* (2020) reported contrasting rainfall trends before and after 1950, based on data from 1901 to 2018, corroborating the decadal-scale shifts identified in the present study. The present study introduces further novelty by detecting precise station-level change points, offering higher temporal resolution than the generalized decadal shifts reported in earlier works.

Homogeneity (absolute test)

In the present study, the classification revealed doubtful annual rainfall series at Edayapatti and Melur, suspect categories at Usilampatti, Gudalore, and Pulipatti, and useful categories elsewhere. SWM rainfall was predominantly suspect, NEM rainfall was mostly useful, and specific months showed varying homogeneity levels. AlSubih *et al.* (2021) observed similar data reliability concerns while identifying downward rainfall trends in Saudi Arabia, indicating that rainfall datasets globally often contain suspect series. The novelty of the present study lies in its comprehensive application of four homogeneity tests (SNHT, Buishand, Pettitt, and Von Neumann ratio tests) across multiple time scales and stations. This methodological thoroughness is uncommon in previous Indian studies and provides a thorough classification that strengthens the robustness of subsequent trend analysis.

MK and MMKY test

The present study, after accounting for serial correlation using MMKY, recorded strong positive trends in May rainfall at Veerapandi ($+4.13^{***}$), June rainfall at Pulipatti ($+4.20^{***}$), annual rainfall at Periyakulam ($+2.31^{**}$), and summer rainfall at Gudalore ($+1.79^{*}$) and Bodi ($+1.78^{*}$). In contrast, negative but non-significant trends were observed at Tirumangalam and Usilampatti. These findings are consistent with Poornima *et al.* (2023), who demonstrated improved long-term rainfall forecast accuracy using Long Short-Term Memory (LSTM), achieving coefficient of determination (R^2) values up to 0.92 over 117 years. Manikandan *et al.* (2024) observed higher detection rates with ITA, identifying 26.6% significant trends, outperforming MK (13.3%) and Simple Linear Regression (SLR) (11.7%), which is comparable to the improved detection by MMKY in the present study. Giri *et al.* (2023) emphasized the importance of addressing serial correlation, supporting the application of MMKY and SQMK methods used here. Additionally, Mehta and Yadav (2021) reported significant monthly, seasonal, and annual rainfall trends across 33 districts of Rajasthan using Sen-Slope Estimator (SSE) and MKT from 1871–2016, further confirming the relevance of high-resolution, robust statistical approaches. Collectively, these studies strengthen the methodological choices of the present analysis, enhancing confidence in localized rainfall assessments.

Regional summary

The present study revealed increasing rainfall trends in western hilly areas (Bodi, Uthamapalayam) and eastern plains (Veerapandi, Periyakulam), with decreasing trends in interior regions (Usilampatti, Tirumangalam, Gudalore). These findings align with Halder *et al.* (2024), who reported a modest annual rainfall decline in Madurai, particularly post-monsoon, and Srivastava and Chinnasamy (2022), who linked declining trends in Madurai to urbanization and reduced infiltration. Singh *et al.* (2021b) observed post-monsoon declines in Madurai

and relative stability in Theni, consistent with this study's spatial patterns. Similarly, Muthiah *et al.* (2024) documented 2.3%, 7.7%, and 44.6% significant annual and seasonal trends in the Vaippar basin, correlating with the mixed trends identified here. Awasthi *et al.* (2024) identified large spatial variability in central India (2.08 mm winter to 3188.21 mm monsoon), resonating with variability across Madurai and Theni. Gupta *et al.* (2024) reported declining monsoon rainfall in Jharkhand (1–3 mm/year shift between 1921–2021), paralleling the increasing variability found in this study. The localized rainfall trends found in Madurai and Theni in this study are largely consistent with those found in earlier research, indicating the necessity of site-specific adaptation measures. The novelty of this study lies in its high-resolution, station-level analysis capturing intra-district rainfall variability, unlike earlier district- or basin-wide studies. It further provides critical insights into local hydrological responses to climate shifts through multi-scale analysis, robust MMKY and homogeneity tests, and detection of serial correlation and station-specific change points. This unprecedented detail for Madurai and Theni districts provides a distinctive contribution to existing research by offering finer spatial insights, emphasizing the need for localized water management and adaptive agricultural planning.

Actionable climate adaptation strategies

Aligned with the goal of actionable insights, spatial-temporal rainfall trends were analyzed to develop region-specific recommendations. Significant trends include a declining SWM rainfall at Usilampatti (prograde < −2.6) and an increasing summer rainfall at Veerapandi (prograde > +3.5), directly informing targeted adaptation strategies. These serve as guidelines for infrastructure planning, crop selection, and water management to enhance agricultural resilience and sustainable resource use.

i. Adaptation recommendations for declining rainfall zones (Usilampatti): Usilampatti shows significant negative rainfall trends during SWM and annual periods (−2.6 to −3.0, with post-2000 stabilization). Recommended actions: shift to short-duration, drought-tolerant crops (millets, black gram, green gram), enhance rainwater harvesting (check dams, percolation and farm ponds, traditional eri tanks), and adopt micro-irrigation (drip, sprinkler) to improve water use efficiency and safeguard productivity.

ii. Adaptation recommendations for increasing rainfall zones (Veerapandi): Veerapandi records strong positive trends in summer and annual rainfall (prograde +3.5). Strategies include expanding summer crops (maize, groundnut, sunflower), introducing short-duration horticulture options (watermelon, cucumber), promoting double or relay cropping, small-scale rainwater storage (check dams, ponds), and improved drainage to prevent waterlogging and maximize yield under higher rainfall.

iii. General recommendations across locations: Broad measures include climate-smart agricultural practices (adaptive sowing, resilient varieties), decentralized water storage, and flexible irrigation. Location-specific trend indicators (Veerapandi +3.5, Usilampatti −2.6) should guide infrastructure (moisture conservation, aquifer recharge systems) and policy planning. Farmer capacity building and localized advisories strengthen resilience to evolving rainfall patterns.

Actionable implications for water resources, agriculture, and policy

This study translates statistical rainfall trends into actionable guidance for water management, agriculture, and climate adaptation. Declining annual rainfall at Madurai (−1.31 mm/year) and SWM reductions (−0.89 mm/year) signal rising water scarcity risks, necessitating groundwater recharge, check dams, and efficient irrigation (drip, sprinkler). In agriculture, reduced SWM rainfall supports drought-tolerant crops and adaptive sowing. Conversely, increasing NEM trends at Theni stations (up to +2.17 mm/year) offer scope for improved rainwater harvesting and expanded post-monsoon cropping. Notable trend shifts, such as 1999 summer change at Bodi, highlight the need for dynamic reservoir management and proactive flood mitigation. These insights strengthen the link between statistical trends and actionable decisions, providing targeted guidance for sustainable water use, agricultural resilience, and regional climate adaptation policies.

Future research and post-2018 climate implications

This study uses rainfall data up to 2018 to assess long-term spatial and seasonal trends. Strong increasing trends were observed at Veerapandi

(Annual MK=+3.51, SS=+13.22; SWM MK=+3.47), Tiruppuvanam (Annual MK=+3.22, SS=+13.79), and Edayapatti (Annual MK=+2.44, SS=+5.83), especially via MMKY and SQMK methods. In contrast, Usilampatti showed significant decreases (Annual MK=−2.66, SS=−13.40; SWM MK=−2.98), notably during NEM. Seasonally, no significant trends appeared in winter, while summer showed positive trends in Andipatti, Bodi, and Uthamapalayam, and declines in September and NEM at Usilampatti (MK=−2.61, SS=−9.27). Methods like PW, TFPW, BCPW, MMKH, MMKY, and SQMK effectively adjusted for serial correlation, confirming trends via both SQMK plots and MK tests. However, the exclusion of post-2018 data limits the understanding of recent shifts driven by climate change, urbanization, and land-use changes. Future research should incorporate post-2018 datasets and apply the same corrected trend detection methodologies to i) validate the persistence of current positive and negative trends, ii) identify any emerging anomalies, and iii) provide updated, actionable insights for climate-resilient water resource management, agriculture, and policy planning.

Linking to global climate change patterns

The observed seasonal and annual rainfall trends in Madurai and Theni districts are consistant with broader global climate change patterns, where increased rainfall variability and shifts in monsoon timing are widely documented in semi-arid regions. The identification of both increasing and decreasing trends reflects global projections of intensified hydrological extremes, including more frequent droughts and localized heavy rainfall events. The temporal shifts and change-points identified in this study allign with the global narrative of climate-induced disruptions in rainfall cycles, emphasizing the importance of regional studies in contextualizing global phenomena. These findings reinforce the need to integrate localized rainfall assessments with national and international climate adaptation frameworks to better anticipate and manage evolving climate risks.

Management implications

The study's findings provide essential evidence for sustainable resource management in Madurai and Theni's semi-arid zones. Identified annual and seasonal rainfall trends, combined with change-point detections, offer early signals of shifting climatic patterns. Local governments and water authorities should integrate these trends into district-level water budgeting, expand rainwater harvesting, modernize irrigation systems, and encourage drought-resilient cropping. Groundwater management strategies must account for detected temporal shifts to ensure long-term sustainability. The use of localized trend data in agricultural advisories can strengthen farmer decision-making, improve cropping outcomes, and build regional climate resilience, supporting rural livelihoods and adaptive capacity.

CONCLUSION

The rainfall pattern analysis in Madurai and Theni districts, Tamil Nadu, revealed significant trends in seasonal, monthly, and annual rainfall over the period 1980 to 2018. The study identified a substantial increase in summer rainfall at six rain gauge stations, along with significant decreases in the SWM season at two stations and in the NEM season at two stations. Serial correlation analysis highlighted autocorrelation in certain months and seasons. Among 357 rainfall series, 17 showed serial correlation, including annual rainfall autocorrelation observed at Tirumangalam, Usilampatti, Gudalore, and Periyakulam. The comprehensive trend analysis demonstrated diverse monthly trends in August and September, indicating the interactions between regional climatic factors. Change-point tests such as the CUSUM and SQMK identified temporal deviations at several stations, especially during monsoon and summer seasons. Noteworthy shifts were detected at Gudalore in 1986, Periyakulam in 1987, and Bodi in 1999. Despite this variability, no SQMK validated change point was statistically significant. Pulipatti marked the most recent temporal adjustments with shifts recorded in 2010 and 2014, underscoring the evolving nature of regional rainfall patterns and climatic complexity. The findings offer key insights for sustainable planning and climate resilience. Madurai shows a slight but notable annual rainfall decline, especially during SWM, posing risks to water resources and monsoon-dependent agriculture**.** Theni's overall rainfall remains stable but with high inter-annual variability, affecting irrigation and cropping schedules. These patterns call for targeted interventions. Madurai requires strategies to mitigate declining rainfall impacts and

extreme events, while Theni needs resilience building against rainfall variability. Continued monitoring and research are essential to guide location-specific adaptation, ensuring sustainable agriculture and water management in semi-arid regions.

AUTHOR CONTRIBUTIONS

P. Sandeep Kumar conceptualized the study, performed data analysis, and drafted the initial manuscript. M. Krishnaveni supervised the research framework and contributed to the interpretation of results and manuscript refinement. D. Sivakumar assisted with methodology validation and supported the statistical analysis. A.S. Madhusudnacharyulu contributed to data processing, graphical visualization, and technical editing. V. Kumar provided domain-specific insights on regional agricultural implications and contributed to result contextualization. All authors reviewed and approved the final manuscript.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
BCPW	Bias-Corrected Pre-Whitening
CRAN	Comprehensive R Archive Network
CV	Coefficient of Variation
ENSO	El Nino Southern Oscillations
IMD	India Meteorological Department

ITA	Innovative Trend Analysis
LSTM	Long Short-Term Memory
MKT	Mann-Kendall Test
mm	Millimeter
MMK	Modified Mann-Kendall
MMKH	Modified Mann-Kendall Test with Hamed and Rao Variance Correction
MMKT	Modified Mann-Kendall Test
MMKY	Modified Mann-Kendall Test with Yue and Wang Correction
NEM	Northeast Monsoon
PW	Pre-Whitening
R^2	Coefficient of Determination
SLR	Simple Linear Regression
SQMK	Sequential Mann-Kendall
SRC	Spearman's Rank Correlation
SRCC	Spearman's Rank Correlation Coefficient
SS	Sen's Slope
SSE	Sen-Slope Estimator
SWM	Southwest Monsoon
TFPW	Trend-Free Pre-Whitening

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ORIGINAL RESEARCH PAPER

Morphometric and genetic characteristics along with ecological adaptation of *Barbodes sellifer* in aquatic management

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ABSTRACT

BACKGROUND AND OBJECTIVES: *Barbodes sellifer* is a freshwater fish species that was recently discovered in the Aneuk Laot Lake ecosystem, Sabang City. Barbodes sellifer, an omnivore, plays a key role in the food web and adapts well to changes in food availability. This species serves a significant ecological function and may benefit local fisheries, yet there is a lack of information about its morphometric and genetic features. The objectives of study were to analyze the morphological traits and genetic diversity of *Barbodes sellifer* populations using a deoxyribonucleic acid barcoding approach. This technique is anticipated to disclose the population structure, genetic variation, and ecological adaptations of the species, supplying a scientific basis for sustainable aquatic management and conservation.

METHODS: This study employed a morphometric and genetic approach comprising morphological analysis and genetic identification based on deoxyribonucleic acid barcoding. *Barbodes sellifer* specimens were collected from several sites within the lake using a purposive random sampling method. Morphological features were assessed via morphometric and meristic measurements, while genetic analysis utilized polymerase chain reaction with specific primers for cytochrome oxidase I. The resulting polymerase chain reaction products were then analyzed using bioinformatics software to identify genetic diversity and phylogenetic relationships among populations.

FINDINGS: Morphological and morphometric analyses confirmed that one of the native fish species of Aneuk Laot Lake is *Barbodes sellifer*. For the first time, this newly documented Indonesian fish has been reported in a lake environment. The morphometric and truss measurements of *Barbodes sellifer* revealed the highest variation in total length (12.52 ± 1.03 centimeters) and standard length (10.07 ± 0.87 centimeters), while the lowest variation was in eye diameter (0.65 ± 0.06 centimeters). Truss morphometric analysis showed the greatest distances in the anterior base of the dorsal fin to the junction of the head and ventral body (3.57 ± 0.40 centimeters), and from the head–dorsal body junction to the anterior base of the ventral fin (2.99 ± 0.37 centimeters). The shortest distances were from the anterior to the posterior base of the anal fin (0.88 ± 0.11 centimeters) and between the dorsal and ventral caudal folds (1.21 ± 0.13 centimeters). The findings indicate important facets of morphological variation in *Barbodes sellifer*, reinforcing studies on population structure and species differentiation. Genetic analysis further confirms this, showing the lake's native fish form a single clade with *Barbodes sellifer*, with 100 percent similarity based on phylogenetic analysis using the Barcode of Life Data System.

CONCLUSION: This study presents the first report on the morphological and genetic characteristics of *Barbodes sellifer* within a lake ecosystem. *Barbodes sellifer* indicates ecological changes, highlighting the need for science-based, sustainable monitoring to maintain aquatic ecosystem balance. The results emphasize the critical role of morphometric and genetic techniques in grasping the population structure and genetic variation of native fish species, providing a scientific foundation for managing aquatic resources. The information obtained can be utilized in the development of conservation strategies and sustainable monitoring of *Barbodes sellifer* habitats in response to threats such as climate change, pollution, and overexploitation.

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INTRODUCTION

Genetic and morphometric approaches in ecology can provide insights into community structure and the responses of biota to natural or anthropogenic changes (Caillon *et al.,* 2018), and are considered crucial fields in biodiversity studies (Caillon *et al.,* 2018; Farré *et al.,* 2013). Genetic diversity is essential for maintaining the health and resilience of ecosystems (Linløkken *et al.,* 2021, Thomson *et al.,* 2021), as it provides the genetic material necessary for natural selection. Morphometric data supplies key insights into the physical characteristics and ecological adaptations of several fish species (Tripathy, 2020). The long-term survival and adaptability of aquatic species heavily rely on genetic diversity, which provides the basic components required for evolutionary processes to happen (Thomson *et al.,* 2021). Likewise, the application of morphometric techniques has enhanced our understanding of fish morphology and its relationship with environmental factors (Wardiatno *et al.,* 2021; Tetelea, 2014). A primary strength of morphometric analysis in fish lies in its capability to quantify diversity among fish communities (Brosse *et al.,* 2021; Tripathy, 2020). The loss of biodiversity may increase vulnerability to environmental stressors, reduce adaptive potential, and elevate extinction risks (Kenchington *et al.,* 2003; Thomson *et al.,* 2021). Research on the native fish of Aneuk Laot Lake remains limited. The presence of native lake fish species was first reported by Nurfadillah *et al.* (2025), identifying *Rasbora* sp. and *Barbodes* sp. as the species found. The genus Barbodes includes a diverse range of freshwater fish species, which are found extensively across Asia, with a notable presence in Indonesia (Dahruddin *et al.,* 2021). This species faces ecological pressure in its native habitat due to the presence of invasive fish that disrupt its role in the food web. In addition, anthropogenic activities pose a significant threat to the stability and diversity of its natural populations (Cerveira *et al.,* 2021). Nonetheless, the range of diversity in this genus is inadequately understood, with particular species being tough to identify based exclusively on their morphological features (Desrita *et al.,* 2021; Lubis *et al.,* 2021; Yanti *et al.,* 2022). Recent studies have utilized deoxyribonucleic acid (DNA) barcoding techniques to clarify the taxonomy of *Barbodes* species, revealing the presence of cryptic diversity within the genus (Dahruddin *et al.,* 2021). Dahruddin *et al*. (2021) conducted a study in which they established a detailed DNA barcode reference library for *Barbodes* species located in the Sundaland biodiversity hotspot, encompassing Java, Sumatra, Borneo, and the Malay Peninsula (Ng and Tan, 2021; Razi *et al.,* 2021). Through extensive sampling and genetic analysis, the researchers successfully identified ten distinct *Barbodes* species in Indonesia, including the spotted barb. One of the native fish species inhabiting Aneuk Laot Lake in Sabang City is believed to belong to the genus *Barbodes*, and is suspected to be *Barbodes sellifer*. This freshwater species is native to various regions of Southeast Asia, including Indonesia, Thailand, and Malaysia, where it inhabits both rivers and lakes (Kottelat and Lim, 2021; Hasan *et al.,* 2024). This species' genetic diversity and population structure were explored in a research project that involved populations gathered from three distinct river systems in Indonesia (Astuti *et al.,* 2020). The results demonstrated genetic differentiation among *B. sellifer* populations from Pasuruan, Yogyakarta, and Cirebon, suggesting that these populations may have diverged over time due to factors such as geographical isolation or local adaptation (Valen *et al.,* 2022). *Barbodes sellifer* exhibits a broader dietary adaptability compared to other sympatric species. According to Nurfadillah *et al.* (2025), *Barbodes* sp. shares similar food resources with other sympatric species such as *Rasbora* sp., yet it employs strategies to avoid direct competition through differences in feeding time or prey size. The variability in genetics empowers native species to adapt to evolving environmental conditions and resist challenges from invasive species (Omoike, 2021). A comprehensive understanding of the morphological characteristics of *Barbodes sellifer* is essential for accurate taxonomic identification and the development of effective conservation strategies. One of the efforts to sustain its population is through the understanding and application of reproductive strategies. According to Musa *et al.* (2023), reproductive strategy is defined as a model that outlines species-specific reproductive traits, incorporating life-history aspects such as the age and size at first sexual maturity, the degree of gonadal maturation, fecundity, and the timing and patterns of spawning. The reproductive strategy characterized by a high reproductive rate allows *Barbodes sellifer* to maintain its population sustainability despite various

ecological pressures such as overfishing, predation, and environmental changes. In addition, this strategy supports the ecological resilience of the species, due to its capacity to adapt to ecological disturbances and contributes to the stability of its community. Comprehensive morphological descriptions facilitate the precise distinction between *B. sellifer* and other species that are morphologically similar, especially within the genus *Barbodes*, recognized for its taxonomic complexity. Accurate species identification is especially crucial in freshwater ecosystems such as Aneuk Laot Lake, the only natural lake on Weh Island, Aceh Province. Aneuk Laot Lake is characterized as a closed basin with no natural inlet or outlet. The lake provides significant ecological, economic, and social benefits (Prianto *et al.,* 2021; Purwoko *et al.,* 2021). It features unique ecological traits and is at risk from several anthropogenic influences, such as alterations in water quality, the arrival of non-indigenous species, and the fragmentation of habitats. In this context, *B. sellifer* may be subject to ecological stressors that could threaten its population viability. Therefore, morphometric analysis integrated with genetic data is necessary to ensure accurate species classification and to detect the possible presence of cryptic species. Defining species accurately is important for evaluating local biodiversity and ecological research in Aneuk Laot Lake, as it also forms a fundamental basis for conserving native species and managing the lake's ecosystem sustainably. Accordingly, the aims of this study is to examine the characteristics of *Barbodes sellifer*; a native species of Aneuk Laot Lake, using molecular (DNA-based) and morphometric approaches in support of conservation strategies for the preservation of local fish species. This study was conducted in the waters of Aneuk Laot Lake, Sabang City, Aceh, Indonesia, during the period 2024–2025.

MATERIALS AND METHODS

Study area

Fish sampling in the waters of Aneuk Laot Lake, Sukakarya Subdistrict, Sabang City, was conducted from March to August 2024 using a purposive random sampling method. Sampling site selection was based on differences in human activities along the lake's riparian zones. The southern riparian zone borders a conservation forest, the western region experiences the impact of farming practices. The eastern area is defined by tourism and residential developments, and the northern riparian zone is largely governed by livestock farming. The geographic coordinates of the sampling locations are shown in (Fig. 1). Molecular (DNA-based) analyses of the fish specimens were carried out at the Laboratory of

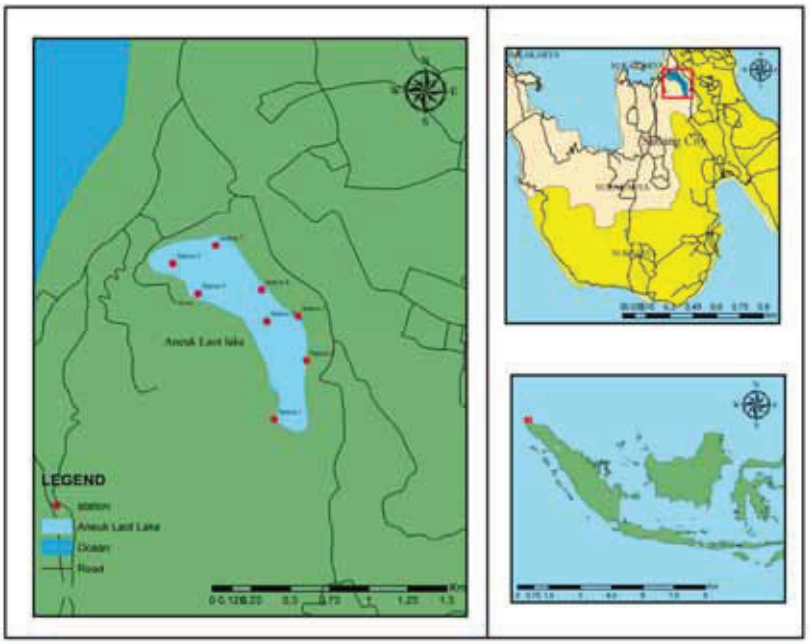

Fig. 1: Geographical location of the study area in Aneuk Laot Lake, Pulau Weh Sabang ,Indonesia

Genetics and Aquatic Biodiversity, Faculty of Marine and Fisheries, Universitas Syiah Kuala. Morphometric measurements were conducted at the Marine Biology Laboratory, Faculty of Marine and Fisheries, Universitas Syiah Kuala.

Research procedure

Fish sampling was conducted using gill nets with mesh sizes of ½ inch, ¾ inch, and 1 inch. Nets were deployed at eight observation stations at a depth of one meter. Each net was set for 24 hours (h), from 07:00 ante meridiem (a.m.) to 06:00 a.m. the following day (Khayra *et al.,* 2016). Catch inspections were performed every six hours. Captured fish samples underwent cleaning and were photographed for the purpose of morphometric analysis. For molecular identification, fin clips were collected from each specimen using sterile scissors, then placed into labeled tubes and preserved in 96 percent (%) ethanol (Joesidawati *et al.,* 2023). The measurement of physico-chemical parameters was conducted both in situ and ex situ, including potential of hydrogen (pH), dissolved oxygen (DO), water transparency, temperature, nitrate, and phosphate.

Morphometric measurement

A total of 50 fish samples were analyzed for both traditional and truss morphometric characteristics using the zeiss efficient navigation (ZEN) 2012 (Blue edition) software (Nur *et al.,* 2022). Descriptive analysis was conducted on morphometric data, which were then presented in tables that include the mean and standard deviation for each measured attribute. According to Batubara *et al.* (2018), twelve traditional morphometric characters were measured (Table 1). Also the morphometric characters of *Barbodes sellifer* is illustrated in Fig. 2.

Truss morphometric measurements were executed following the approach described by Wijayanti *et al*. (2017), with the measurements extending from the tip of the snout to the base of the caudal fin. A total of 10 anatomical landmarks were used as reference points, resulting in 21 truss morphometric characters. These are illustrated in (Fig. 3) and detailed in Table 2.

DNA extraction

DNA isolation involves the breakdown (lysis) or separation of DNA from solid components such as cellulose and proteins, followed by DNA purification (Grewe *et al.,* 1993). The extraction process consisted of two main stages: the first stage (cell lysis) and the second stage (DNA separation), performed using the cetyltrimethylammonium bromide (CTAB) method. In the first stage, 700 microliters (µL) of CTAB reagent and 3 µL of proteinase K were used. Subsequently, the samples were placed in an oven and incubated for 12 h at a temperature of 60 degrees Celsius (°C). The second stage began by removing the samples from the oven and adding 700 µL of chloroform: isoamyl alcohol (CIA), followed by vigorous manual shaking for 15 seconds. The mixture was then centrifuged at 11,000 revolutions per minute (rpm) for 15 minutes. Subsequently, 550–600 µL of the supernatant was transferred to a 1.5 mililiters (ml)

Table 1: Twelve morphometric characters measured using the conventional method

No.	Code	Character	Description
1	TL	Total length	Distance from the tip of the snout to the end of the caudal fin.
2	SL	Standard length	Distance from the tip of the snout to the base of the caudal peduncle.
3	HL	Head length	Distance from the tip of the snout to the posterior edge of the operculum.
4	CPL	Caudal peduncle length	Distance from the end of the anal fin to the base of the caudal fin.
5	SNL	Snout length	Distance from the tip of the snout to the anterior edge of the eye.
6	DFD	Dorsal fin depth	Vertical distance from the base to the tip of the dorsal fin.
7	DFBL	Dorsal fin base length	Distance from the anterior to the posterior base of the dorsal fin.
8	ED	Eye diameter	Horizontal diameter of the eye.
9	CPD	Caudal peduncle depth	Vertical distance from the dorsal to the ventral edge of the caudal peduncle.
10	BD	Body depth	Vertical distance from the dorsal to the ventral side of the body.
11	PFL	Pectoral fin length	Distance from the base to the tip of the pectoral fin.
12	VFL	Pelvic fin length	Distance from the base to the tip of the pelvic fin.

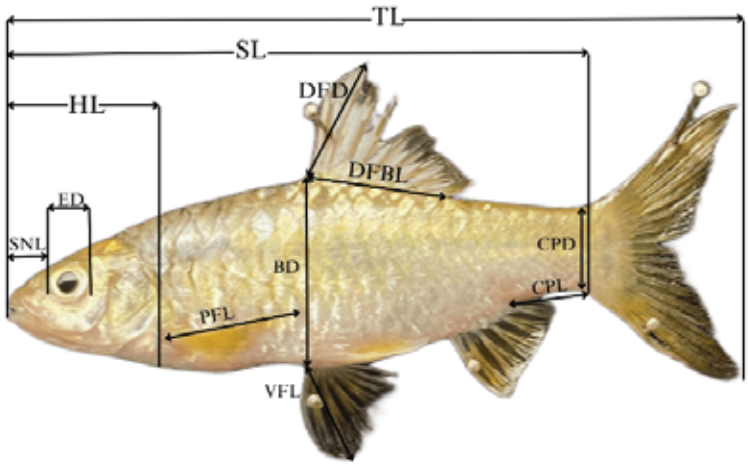

Fig. 2: Measurement of morphometric characters using the conventional method

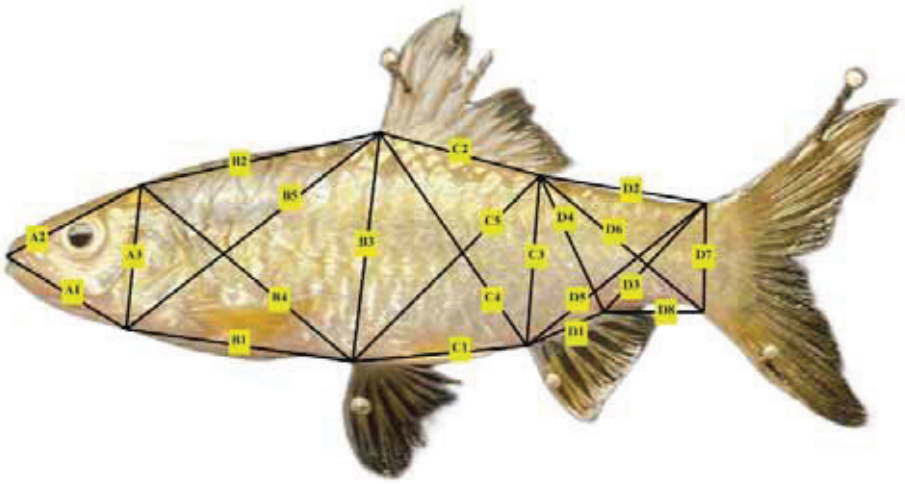

Fig. 3: Truss morphometric characters measured (Personal documentation), the ten anatomical landmarks used for truss morphometric measurements include:(1) the anterior tip of the snout, 2) the junction between the head and the ventral body, 3) the junction between the head and the dorsal body, 4) the anterior base of the pelvic fin, 5) the anterior base of the dorsal fin, 6) the anterior base of the anal fin, 7) the posterior base of the dorsal fin, 8) the posterior base of the anal fin, 9) the origin of the dorsal caudal peduncle, and 10) the origin of the ventral caudal peduncle (Wijayanti *et al.,* 2017)

microtube. An equal volume of ethanol (ETOH) was added to the supernatant, followed by a rapid spin, and subsequently, the samples were placed in a freezer freezer at –20 °C for 2 h. Once the incubation was complete, the samples underwent centrifugation once more at 13,000 rpm for 15 minutes. Finally, the supernatant was discarded, and the resulting pellet was air-dried for 1–2 h before being resuspended in 50 µL of double-distilled water (ddH_2O) (Fadli *et al.,* 2024).

DNA amplification

DNA amplification was carried out in vitro using the polymerase chain reaction (PCR) technique with the forward primer Fish F1 (5'-TCAA AAC AAC AAC CAC AAA GAC ATT GGG AC-3') and the reverse primer Fish R1 (5'-TAG ACT TCT GGG TGG CCA AAG AAT CA-3'), which are suitable for fish sample amplification (Ward *et al.,* 2005). The PCR mixture consisted of 2 µL of DNA template, 8.5 µL of ddH_2O, 1 µL of cytochrome c oxidase subunit I (COI) Fish F1 primer, 1 µL of COI

Table 2: Truss morphometric characters of *Barbodes sellifer*

No.	Region	Code	Description
1	Head region	A1	Distance from the snout tip to the ventral head-body junction
2		A2	Distance from the snout tip to the dorsal head-body junction
3		A3	Distance from the dorsal to the ventral head-body junction
4	Anterior body region	B1	Distance from the ventral head-body junction to the anterior base of pelvic fin
5		B2	Distance from the dorsal head-body junction to the anterior base of dorsal fin
6		B3	Distance from the anterior base of dorsal fin to the anterior base of pelvic fin
7		B4	Distance from the dorsal head-body junction to the anterior base of pelvic fin
8		B5	Distance from the anterior base of dorsal fin to the ventral head-body junction
9	Posterior body region	C1	Distance from the anterior base of pelvic fin to the anterior base of anal fin
10		C2	Distance from the anterior to the posterior base of dorsal fin
11		C3	Distance from the posterior base of dorsal fin to the anterior base of anal fin
12		C4	Distance from the anterior base of dorsal fin to the anterior base of anal fin
13		C5	Distance from the posterior base of dorsal fin to the anterior base of pelvic fin
14	Caudal region	D1	Distance from the anterior to the posterior base of anal fin
15		D2	Distance from the posterior base of dorsal fin to the dorsal caudal peduncle origin
16		D3	Distance from the dorsal caudal peduncle origin to the posterior base of anal fin
17		D4	Distance from the posterior base of dorsal fin to the posterior base of anal fin
18		D5	Distance from the anterior base of anal fin to the dorsal caudal peduncle origin
19		D6	Distance from the posterior base of dorsal fin to the ventral caudal peduncle origin
20		D7	Distance from the dorsal to the ventral caudal peduncle origin
21		D8	Distance from the posterior base of anal fin to the ventral caudal peduncle origin

Fish R1 primer, and 12.5 µL of ready-to-use master mix. Amplification was performed using a Sensuquest Labcycler (SensoQuest GmbH, Hannah-Vogt-Str.1) for a total of 30 cycles. Each PCR cycle included the following steps pre-denaturation at 95 °C for 2 minutes, denaturation at 94 °C for 45 seconds, annealing at 47.9–60 °C for 45 seconds, extension at 72 °C for 60 seconds, and final extension at 72 °C for 10 minutes, followed by a hold at 4 °C to terminate the reaction (Rahayu *et al.,* 2023).

DNA electrophoresis and sequencing

Electrophoresis is a technique for chemical separation that relies on the varying migration speeds of molecules when subjected an electric field (Sumarlin *et al.,* 2020). The electrophoresis process began with the preparation of an agarose gel stained with 2 µL of red stain, which served as the medium for analyzing the electrophoresis results. The electrophoresis products were visualized using a ultraviolet transilluminator (UVITEC) at 100 volts for 30 minutes. The presence of a single, distinct band around 500–700 base pairs (bp) indicated successful PCR products. PCR products that showed clear visualization were deemed suitable for sequencing. PCR products confirmed as positive were sent to First BASE Laboratories, Malaysia, for nucleotide sequencing using the Sanger method (Sanger *et al.,* 1977).

Data analysis

The sequences used for comparison are selected from verified and geographically relevant BIN (Barcode Index Number) clusters to ensure ecological and taxonomic compatibility with local samples. The sequence used as a reference is the COI sequence. Two software programs, Molecular Evolutionary Genetics Analysis (MEGA) XI and DnaSP 6.12.03, were employed for the sequence analysis. In MEGA, the analysis included sequence editing, trimming, and alignment using ClustalW. Sequence editing was performed to assess the quality of sequences obtained from the sequencing process. Once the editing was completed, the sequences were aligned and subsequently trimmed to make sure that only the functional mitochondrial sequences were preserved. Following the identification of functional sequences, a basic local alignment search tool (BLAST) search was conducted using the national center for biotechnology information (NCBI) database and the barcode of life data system (BOLD), systems database for species identification. BLAST results with sequence similarity ranging from 97% to 100% to the query DNA were selected for further analysis in molecular

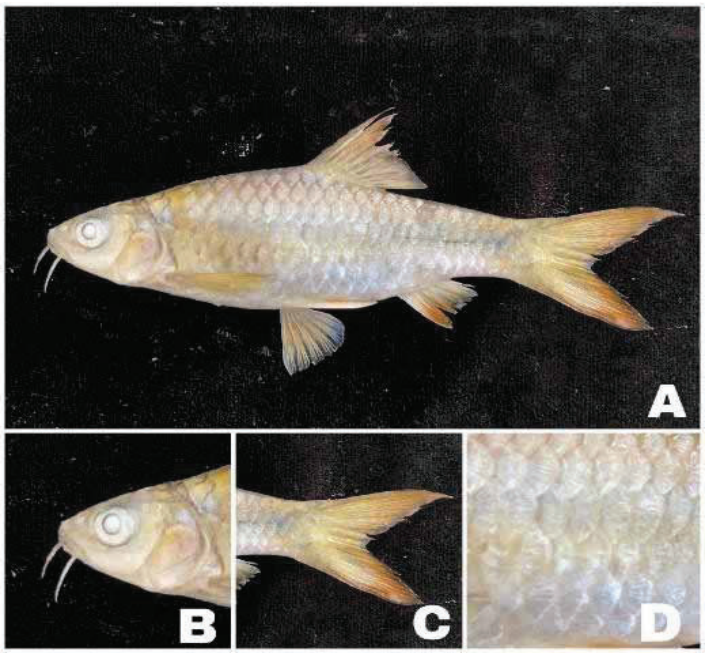

Fig. 4: Morphological characteristics of *Barbodes sellifer* (A. fusiform body shape; B. forked caudal fin; C. subterminal mouth type; D. ctenoid scale type)

identification (Tamura *et al.,* 2013). Phylogenetic tree construction was performed using the neighbor-Joining (NJ) method with the Kimura 2-Parameter (K2P) model to define intra-species, genus, and family-level differences. Bootstrap analysis involving 1,000 replicates was performed to determine the statistical backing for the inferred phylogenetic tree. The K2P model was employed to calculate genetic distances, again using 1,000 bootstrap replicates.

RESULTS AND DISCUSSION

Morphological and morphometric characteristics of Barbodes sellifer

Based on morphological and morphometric observations (Fig. 4), the fish species captured in the waters of Aneuk Laot Lake were identified as *Barbodes sellifer.* Species identification referred to the study by Kottelat and Lim (2021), which described two new cryptic species of *Barbodes* within the *Barbodes binotatus* complex. Cryptic species are morphologically similar forms that can nevertheless be distinguished genetically (Borsa *et al.,* 2018). Morphologically, *B. sellifer* exhibits a fusiform body shape—elongated, laterally compressed, and upright. The caudal fin is forked, and the scales are ctenoid, appearing square and comb-like. A key characteristic of this species is the existence of a dark (black) blotch located between the anal and caudal fins. Other important features consist of a body color that varies from silvery to brownish, as well as yellow to orange pigmentation on the dorsal, anal, and caudal fins. Additionally, this species possesses two pairs of barbels around the mouth region. The morphological characteristics used to identify *Barbodes sellifer* specimens captured in Aneuk Laot Lake are presented in Table 3 and illustrated in (Fig. 4).

Barbodes sellifer exhibits distinctive morphological characteristics, including a yellow and silver body coloration, yellow eyes with black pupils. The mouth is positioned subterminally, and the species possesses a pair of barbels. The attributes mentioned are in agreement with the results presented by Kottelat and Lim (2021), who noted that *Barbodes sellifer* has a body and head that are dark yellowish-brown. This species belongs to the family Cyprinidae, which is characterized by a fusiform or torpedo-shaped body and a forked caudal fin. This is in accordance with Budiantoro and Noor (2023), who stated that members of the Cyprinidae family generally have a fusiform body posture—elongated, flattened, and

Table 3: Morphological Characteristics of *Barbodes sellifer* (Kottelat and Lim, 2021)

No.	Morphological Character	*Barbodes sellifer* (Primary data)	*Barbodes sellifer*
1	Body shape	Fusiform	Fusiform
2	Caudal fin shape	Forked	Forked
3	Mouth type	Subterminal	Subterminal
4	Scale type	Ctenoid	Ctenoid

Table 4: Conventional morphometric characteristics of *Barbodes sellifer*

No	Character	Minimum range (cm)	Maximum range (cm)	Mean ± SD
1	TL	7.11	12.52	9.88 ± 1.03
2	SL	5.57	10.07	7.84 ± 0.87
3	HL	1.31	2.59	1.91 ± 0.22
4	CPL	0.76	2.03	1.26 ± 0.22
5	SNL	0.30	0.81	0.50 ± 0.12
6	DFD	1.30	2.46	1.67 ± 0.20
7	DFBL	1.06	1.79	1.36 ± 0.17
8	ED	0.36	0.65	0.49 ± 0.06
9	CPD	0.90	1.63	1.28 ± 0.15
10	BD	1.78	3.26	2.61 ± 0.3
11	PFL	1.19	2.16	1.73 ± 0.21
12	VFL	0.85	1.54	1.16 ± 0.14

upright—with large scales and forked tails.

The results of conventional and truss morphometric measurements of *Barbodes sellifer* are presented in Table 4. The highest value was recorded for total length , with a maximum of 12.52 centimeters (cm) and an average of 9.88 ± 1.03 cm. This was followed by SL, with a maximum of 10.07 cm and an average of 7.84 ± 0.87 cm. The lowest value was found in eye diameter (ED), with a measurement of 0.65 cm and an average of 0.49 ± 0.06 cm, followed by snout length (SNL), which measured 0.81 cm with an average of 0.50 ± 0.12 cm.

The results of truss morphometric character measurements of *Barbodes sellifer* are presented in Table 5. The greatest measurement was documented for the distance between the anterior base of the dorsal fin and the junction of the head and ventral body (B5), measuring 4.74 cm, with an average of 3.57 ± 0.40 cm. This was followed by the distance from the junction of the head and dorsal body to the anterior base of the ventral fin (B4), with a value of 4.00 cm and an average of 2.99 ± 0.37 cm. The lowest measurement was observed in the distance between the anterior and posterior base of the anal fin (D1), which was 1.33 cm with an average of 0.88 ± 0.11 cm. Next was the distance from the dorsal to ventral caudal fold (D7), which measured 1.48 cm with an average of 1.21 ± 0.13 cm.

The comprehensive evaluation of the truss morphometric technique in conjunction with standard methods suggests that *Barbodes sellifer* individuals inhabiting lake areas display slight discrepancies in the location of the distinctive black spot on the caudal peduncle relative to those found in the Cerucuk River, Belitung (Hasan *et al*., 2024), indicating potential local adaptation. Truss measurements show an elongation of the mid-body and a narrowing of the caudal peduncle, likely as a response to the calm aquatic environment, which does not require high swimming speed. Results from conventional and truss morphometric evaluations of *Barbodes sellifer* reveal significant differences. The highest variation was observed in the total length, measuring 12.52 cm with a standard deviation of 1.03 cm, followed by the SL at 10.07 cm with an SD of 0.87 cm. The lowest variation was recorded in the ED, measuring 0.65 cm with an SD of 0.06 cm. According to a study by Hasan *et al*. (2024), *Barbodes sellifer* was found in Belitung, with total length (TL) and SL recorded at 131.65 mm and 79.0 mm, respectively. The differences in fish size may be attributed to variations in sampling locations and environmental conditions. This corresponds with the conclusions drawn by Nurtira *et al*. (2021), who noted that the

Table 5: Traditional truss morphometric measurements of *Barbodes sellifer*

No.	Character	Minimum range (cm)	Maximum range (cm)	Mean ± SD
1	A1	1.05	2.22	1.52 ± 0.24
2	A2	1.15	2.23	1.65 ± 0.23
3	A3	1.14	2.12	1.61 ± 0.19
4	B1	1.78	3.47	2.47 ± 0.30
5	B2	1.83	3.55	2.69 ± 0.34
6	B3	1.78	3.22	2.62 ± 0.30
7	B4	2.09	4.00	2.99 ± 0.37
8	B5	2.48	4.74	3.57 ± 0.40
9	C1	1.45	2.54	2.12 ± 0.25
10	C2	1.05	1.82	1.35 ± 0.17
11	C3	1.37	2.50	1.95 ± 0.23
12	C4	2.08	3.60	2.83 ± 0.30
13	C5	1.87	3.37	2.80 ± 0.32
14	D1	0.70	1.33	0.88 ± 0.11
15	D2	1.80	3.10	2.45 ± 0.28
16	D3	1.18	2.22	1.76 ± 0.22
17	D4	1.47	2.52	1.95 ± 0.23
18	D5	1.86	3.15	2.59 ± 0.27
19	D6	1.97	3.60	2.80 ± 0.34
20	D7	0.86	1.48	1.21 ± 0.13
21	D8	0.68	1.80	1.18 ± 0.20

size of fish in various studies can be impacted by the conditions of their habitats. Similarly, Almasari *et al.* (2021) noted that fish size variation is also affected by food availability, environmental conditions, and habitat differences.

DNA barcoding of Barbodes sellifer

The DNA barcoding analysis in this study successfully amplified five samples, each producing a DNA fragment of 642 bp, which were validated to be free of stop codons, deletions, or insertions. The base pairs obtained indicate functional sequences associated with the mitochondrial COI gene. This fragment length is consistent with previous studies, including Fadli *et al.* (2020) who reported 639 bp, Kainama *et al.* (2023) with a range of 616–658 bp, and Bingpeng *et al.* (2018) with 655 bp. The consistency of fragment length is crucial, as Imtiaz *et al.* (2017) stated that sequences within this length range are recognized as an adequate standard for molecular identification at the species level in fish. These conclusions bolster the reliability of the techniques utilized and indicate that the fragment length achieved fulfills the standards for accurate identification at the species level. The uniformity of fragment length with prior studies also suggests that the COI gene region targeted in this study serves as a stable marker for fish biodiversity research (Chen *et al.,* 2015; Hubert *et al.,* 2015; Tsoupas *et al.,* 2022; Ude *et al.,* 2020; Ali *et al.,* 2020). All five samples were successfully identified using the BLAST method against two molecular databases, GenBank and BOLD, with sequence similarity percentages ranging from 96% to 100% (Table 6). All sequences showed the closest alignment with *B. sellifer*, confirming their status as members of this species. Notably, one sample also exhibited 96% similarity to *Barbodes banksi*, indicating a minor level of genetic variation and suggesting potential overlap or misidentification among closely related taxa. Inconsistencies were detected in species classifications among molecular databases, whereas GenBank recognized the match as *Barbodes* sp. ACHa6, the BOLD database assigned the same sequence to *Barbodes sellifer*. These discrepancies point to ongoing challenges in taxonomy and indicate broader concerns within reference databases, including insufficient taxon representation and incorrectly annotated entries (Bignotto *et al.,* 2025). These findings highlight the underlying taxonomic uncertainty within the *Barbodes* genus, which is compounded by the high degree of morphological similarity among species in the Cyprinidae family (Kottelat, 2013; Ren *et al.,* 2020). The occurrence of close genetic relationships with

Table 6: BLAST analysis of COI marker based on % query and % identity from NCBI, and % similarity from BOLD system

Species detection	NCBI			BOLD	
	% Query	% BLAST	Accession Number	% Similarity	Boldsystem Index Number (BIN)
Barbodes sellifer				100%	BOLD:ACC0849
Puntius brevis	100	99	HM345937.1	99%	BOLD:ACC0849
Barbodes sp. ACHa6	100	100	MN916432.1		
Barbodes bankis	100	96	ON668407.1	96%	BOLD:ADP3053
Barbodes sellifer				100%	BOLD:ACC0849
Puntius brevis	100	99	HM345937.1	99%	BOLD:ACC0849
Barbodes sp. ACHa6	100	100	MN916432.1		
Barbodes bankis	100	96	ON668407.1	97%	BOLD:ADP3053
Barbodes sellifer				100%	BOLD:ACC0849
Puntius brevis	100	99	HM345937.1	96%	BOLD:ACC0849
Barbodes sp. ACHa6	100	100	MN916432.1		
Barbodes bankis	100	96	ON668407.1	96%	BOLD:ADP3053
Barbodes sellifer				100%	BOLD:ACC0849
Puntius brevis	100	99	HM345937.1	99%	BOLD:ACC0849
Barbodes sp. ACHa6	100	100	MN916432.1		
Barbodes bankis	100	96	ON668407.1	96%	BOLD:ADP3053
Barbodes sellifer				100%	BOLD:ACC0849
Puntius brevis	100	99	HM345937.1	99%	BOLD:ACC0849
Barbodes sp. ACHa6	100	100	MN916432.1		
Barbodes bankis	100	96	ON668407.1	96%	BOLD:ADP3053

other species, including *Puntius brevis* and *B. banksi*, complicates the process of species delimitation and prompts inquiries regarding the precision of existingspecies boundaries. This pattern may reflect either low regional genetic diversity within *B. sellifer* populations—possibly due to restricted gene flow or population bottlenecks—or the presence of cryptic diversity, with genetically distinct lineages not yet formally described (Hebert *et al.,* 2004; Gomes *et al.,* 2015). The low genetic divergence noted could alternatively be linked to factors including recent evolutionary radiation, incomplete lineage sorting, or the constraints of the mitochondrial COI gene's resolving power. These issues are well-documented in barcoding studies of closely related freshwater fishes and emphasize the need for integrative taxonomic approaches (Sandall *et al.,* 2023). Importantly, these taxonomic ambiguities have significant implications for biodiversity monitoring and conservation planning. Misidentification or under-recognition of species diversity may lead to inaccurate assessments of conservation status, misallocation of management resources, and an incomplete understanding of ecosystem dynamics—particularly in Southeast Asia, a region recognized for its rich yet vulnerable aquatic biodiversity (Shet *et al.,* 2017). To conduct further analysis, including calculating genetic distance, only samples that were morphologically identified and corresponded with the top three reference sequences—those with the lowest E-value (0) and the highest identity percentage (97–100%)—were used. Generally, the similarity threshold used for fish species identification based on molecular data is a minimum of 97%, as stated by (Wong and Hanner, 2008; Panprommin *et al.,* 2021). These selected references were subsequently used to reconstruct a phylogenetic tree and calculate genetic distances based on the Kimura 2-Parameter model. Furthermore, sequences from other *Barbodes* species were incorporated for comparative analysis in the phylogenetic reconstruction.

The constructed NJ tree based on the Kimura 2-Parameter (K2P) model with 1000 bootstrap replicates clearly illustrates the divergence among species within the genus *Barbodes* (Fig. 5). Based on BLAST results, reference data from *Puntius brevis* were also included in the phylogenetic analysis. The tree produced shows that *Barbodes* fails to create a monophyletic clade, instead branching into various lineages, which illustrates the paraphyletic nature of both *Barbodes* and *Puntius*. This non-monophyletic pattern indicates that the current taxonomic grouping

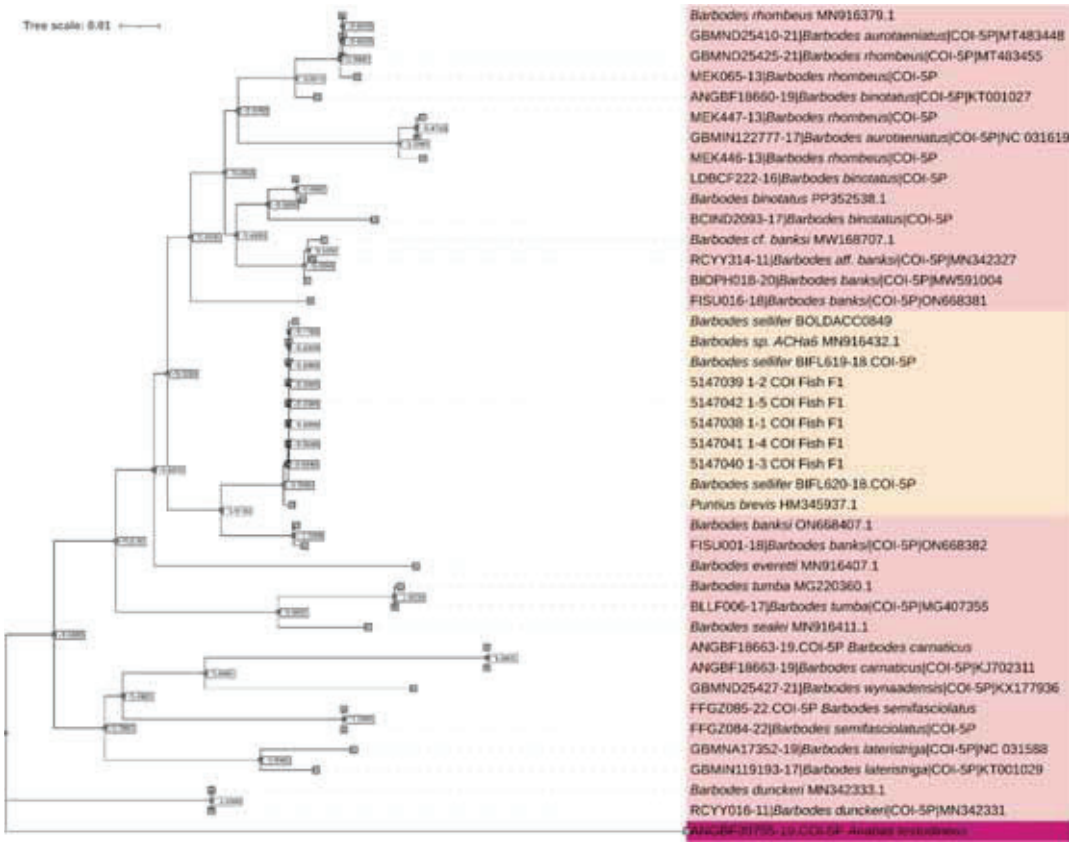

Fig. 5: Phylogenetic tree of species within the genus Barbodes and related species based on mitochondrial COI gene using the NJ method with the K2P model and 1000 bootstrap replicates

does not accurately reflect evolutionary relationships. This result corresponds with prior studies (Ren *et al*., 2020; Kottelat, 2013), which stress the importance of conducting a molecular-based taxonomic revision to clarify the ambiguous boundaries between these genera. Significantly, the tree structure and extensive genetic patterns imply the likelihood of cryptic species being present within the *Barbodes sellifer* lineage. Although all five Aceh samples were identified as *B. sellifer*—confirmed through DNA barcoding and showing 100% similarity with a sequence (*Barbodes* sp. ACHa6) recorded prior to the species' formal description—the paraphyletic arrangement raises the possibility of hidden genetic diversity or taxonomic misclassification within this group. Historically, *B. sellifer* was misidentified as *B. banksi* due to morphological resemblance, which underscores the challenge of distinguishing morphologically similar but genetically distinct taxa. Misidentifications of this nature are indicative of cryptic species, particularly within freshwater groups such as *Barbodes*, where convergent morphology is common. In this study, the five Aceh samples clustered tightly with *Barbodes sellifer* and *Barbodes* sp. ACHa6, supported by high bootstrap values (>85%), confirming their identity as *B. sellifer*. The inclusion of *Puntius brevis* in a closely related clade with *Barbodes sellifer* and *Barbodes* sp. ACHa6 further highlights the taxonomic complexity and reinforces the need for integrative taxonomic approaches. Notably, *Barbodes* sp. ACHa6, submitted by Sobri (unpublished, 2020), was previously used in the identification of *Barbodes binotatus* (Sobri *et al.*, 2021), adding to the significance of this lineage as a reference point. Consistent with observations from Sobri *et al*. (2021) and Ren *et al*. (2020), the COI-based phylogenies repeatedly reveal that the genus

Table 7: Genetic distances between fish samples in this study and reference sequences from GenBank and BOLD systems

No	ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	5147038_1-1_COI_Fish_F1																									
2	5147042_1-5_COI_Fish_F1	0,00																								
3	5147041_1-4_COI_Fish_F1	0,00	0,00																							
4	5147039_1-2_COI_Fish_F1	0,00	0,00	0,00																						
5	5147040_1-3_COI_Fish_F1	0,00	0,00	0,00	0,00																					
6	Barbodes_sellifer_BIFL619-18.COI-5P	0,00	0,00	0,00	0,00	0,00																				
7	Barbodes_sellifer_BIFL620-18.COI-5P	0,00	0,00	0,00	0,00	0,00	0,00																			
8	Barbodes_sellifer_BOLDACC0849	0,00	0,00	0,00	0,00	0,00	0,00	0,00																		
9	BCIND2093-17|Barbodes_binotatus|COI-5P	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,09																	
10	Barbodes_binotatus_PP352538.1	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,07	0,04																
11	MEK065-13|Barbodes_rhombeus|COI-5P	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,06	0,05															
12	Barbodes_rhombeus_MN916379.1	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,06	0,05	0,01														
13	Barbodes_dunckeri_MN342333.1	0,13	0,13	0,13	0,13	0,13	0,13	0,13	0,13	0,15	0,14	0,15	0,15													
14	BLLF006-17|Barbodes_tumba|COI-5P|MG407355	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,14	0,12	0,12	0,14												
15	Barbodes_sp._ACHa6_MN916432.1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,06	0,08	0,08	0,13	0,12											
16	Barbodes_cf._banksi_MW168707.1	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,06	0,04	0,05	0,05	0,14	0,13	0,07										
17	Barbodes_banksi_ON668407.1	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,09	0,07	0,09	0,08	0,12	0,12	0,04	0,07									
18	GBMIN122777-17|Barbodes_aurotaeniatus|COI-5P|NC_031619	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,09	0,08	0,08	0,07	0,13	0,13	0,10	0,08	0,09								
19	ANGBF18663-19|Barbodes_carnaticus|COI-5P|KJ702311	0,17	0,17	0,17	0,17	0,17	0,17	0,18	0,18	0,20	0,19	0,19	0,18	0,18	0,18	0,17	0,18	0,18	0,17							
20	FFGZ085-22.COI-5P_Barbodes_semifasciolatus	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,16	0,15	0,15	0,15	0,14	0,14	0,14	0,15	0,14	0,15	0,16						
21	GBMND25427-21|Barbodes_wynaadensis|COI-5P|KX177936	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,19	0,17	0,17	0,17	0,17	0,16	0,15	0,18	0,15	0,16	0,13	0,12					
22	Barbodes_everetti_MN916407.1	0,10	0,10	0,10	0,10	0,10	0,10	0,11	0,11	0,12	0,09	0,12	0,11	0,16	0,15	0,10	0,12	0,10	0,13	0,19	0,18	0,18				
23	Barbodes_sealei_MN916411.1	0,10	0,10	0,10	0,10	0,10	0,10	0,11	0,10	0,13	0,12	0,12	0,12	0,15	0,05	0,10	0,12	0,12	0,14	0,19	0,14	0,16	0,15			
24	Puntius_brevis_HM345937.1	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,01	0,09	0,07	0,08	0,08	0,13	0,13	0,00	0,07	0,04	0,11	0,17	0,14	0,16	0,10	0,11		
25	ANGBF30755-19.COI-5P_Anabas_testudineus	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,26	0,25	0,28	0,27	0,23	0,30	0,25	0,26	0,24	0,25	0,29	0,25	0,27	0,26	0,29	0,25	

Barbodes fails to form a strictly monophyletic lineage. The combination of these patterns necessitate a thorough phylogenomic reevaluation to address taxonomic ambiguities, elucidate evolutionary connections, and guarantee precise biodiversity evaluation within this intricate genus.

An extended examination was carried out to compute genetic distances both within species and across species utilizing the K2P model. Genetic distances were compared between the samples from this study and the closest clade identified in the phylogenetic analysis, which includes *Barbodes* sp. ACHa6, *Barbodes sellifer*, *Puntius brevis*, and several other *Barbodes* species, as shown in Table 7. The overall average genetic distance was 0.11 ± 0.01. The average genetic distance overall was calculated to be 0.11 ± 0.01. Among the five study samples, including sequences from *Barbodes* sp. ACHa6 and *Barbodes sellifer*, the within-species genetic distance was 0. In contrast, the smallest between-species distance was observed between *Barbodes* sp. ACHa6 and *Barbodes banksi*, with a value of 0.04. At the individual level, the smallest genetic distance was 0, either among study samples or between study samples and *Barbodes* sp. ACHa6 sequences, while the largest distance was between *Puntius brevis* and the designated outgroup (Table 7). To compare across different taxonomic units, Ali *et al.* (2020) used K2P as a model to estimate genetic divergence, showing an increase in genetic distance with higher taxonomic ranks. The study conducted by Ali *et al.* (2020) involved calculating distances at the species, genus, family, and order levels. Conversely, this study limited its genetic distance calculations to the genus level, producing results that matched those previously documented by (Ali *et al.,* 2020; Wang *et al.,* 2018). Several studies have used a genetic distance of 2–3% as a threshold to indicate species-level differentiation (Zhang and Hanner, 2011; Kenchington *et al.,* 2017). Accordingly, the >2% distance observed in this study is considered indicative of interspecific genetic divergence (Teramura *et al.,* 2022). The low genetic distance between the samples and *Barbodes sellifer* supports their identification as *Barbodes sellifer*. Additionally, *Barbodes* sp. ACHa6 also showed low genetic divergence from *Barbodes sellifer*, suggesting it may represent the same species. In *Barbodes sellifer*, the intraspecific genetic variation was determined to be low, as indicated by a genetic distance value of 0 among the sampled individuals. A higher level of intraspecific variation typically indicates greater genetic diversity within a population, which supports ecological adaptability. Conversely, the lack of variation noted in this study indicates a restricted capacity for adaptation. In this case, the low intraspecific variation reflects that *B. sellifer* has a low level of genetic diversity in the sampled population, implying reduced capacity for

adaptation to environmental changes, such as climate shifts or anthropogenic impacts. This absence of variation might be linked to the geographical isolation present in the waters of Aneuk Laot Lake, which could limit gene flow between different populations. Limited gene flow can lead to genetic homogeneity and may increase the species' vulnerability to environmental disturbances. The *Barbodes sellifer* sequence in the BOLD database was collected from the Montala River (*Krueng Aceh*), and Sobri *et al.* (2021) explicitly indicated the location using the code "Acheh," confirming the sample's origin from Aceh. Interestingly, the placement of *Puntius brevis* within the same clade as *Barbodes sellifer* raises questions. According to the genetic distance analysis, the minimum distance observed between *Puntius brevis* and one of the *Barbodes sellifer* sequences was 0. The clustering of *Puntius brevis* within the same clade as *Barbodes sellifer* in the phylogenetic analysis is likely the result of taxonomic misidentification or insufficient genetic resolution. BLAST analysis revealed that *P. brevis* reference sequences showed a genetic distance of 0 from the samples analyzed in this study, indicating identical or nearly identical COI sequences. The consistent grouping of these sequences with *B. sellifer*, rather than creating a separate lineage, lends support to the hypothesis that *P. brevis* could have been incorrectly classified or annotated in various databases. This finding, along with the small genetic distances observed among *Barbodes* sp. ACHa6, *P. brevis*, and *B. sellifer*, highlights the complexity within the *Barbodes* group. Such complexity is apparent in the discrepancies found in genetic databases, the structures of phylogenetic trees, and the annotations at the species level. The overlap suggests that *P. brevis*, as represented in some molecular records, may actually correspond to *B. sellifer*, or that the COI gene alone is insufficient to resolve species boundaries in this group due to shared haplotypes, recent divergence, or incomplete lineage sorting—factors commonly observed in the Cyprinidae family. These problems emphasize the significance of adopting integrative and multi-locus methods to advance species delimitation and improve taxonomic accuracy in this taxonomically intricate genus.

This study highlights the importance of integrating molecular and morphological approaches for accurate taxonomic identification of fish species. Integrating morphological and genetic data significantly enhances species identification in complex aquatic ecosystems by providing a more accurate and multidimensional understanding of biodiversity. Although DNA barcoding using the mitochondrial COI gene has proven effective in detecting species and assessing genetic diversity, this method presents limitations—particularly when reference databases are incomplete or contain misannotated species (Bignotto *et al.,* 2025; Collins and Cruickshank, 2013). In such scenarios, depending exclusively on molecular data may result in taxonomic errors, particularly in freshwater ecosystems that exhibit taxonomically complex. Therefore, morphological confirmation remains essential to cross-validate genetic results and to detect subtle phenotypic differences that may not be reflected in COI sequences. This method is particularly important for groups such as Cyprinidae, characterized for their morphological convergence and hidden diversity. Integrative taxonomy, which combines morphological, genetic, and ecological data, has now become the gold standard in biodiversity studies (Nicolas, 2024). Within the framework of this study, the application of both morphological and molecular techniques produced a noteworthy conclusion: all five fish samples collected from Aceh were unmistakably recognized as the species *Barbodes sellifer*. This identification was supported not only by morphological consistency but also by molecular evidence showing 100% sequence similarity with *Barbodes* sp. ACHa6, a sequence collected in 2020—prior to the formal description of *B. sellifer* by Kottelat and Lim (2021). This finding demonstrates the power of integrative taxonomy in uncovering the historical and geographic distribution of newly described species and highlights the importance of re-evaluating previous classifications that may have been based solely on morphological data. Furthermore, species complexes like the one associated with *B. sellifer* are often found in freshwater habitats, especially within the Cyprinidae family. In such contexts, integrative taxonomy plays a vital role in resolving taxonomic ambiguities, enhancing the accuracy of biodiversity assessments, and guiding adaptive resource management. Precise identification of species guarantees that conservation efforts are ecologically suitable and that any misidentified or neglected species are not excluded from biodiversity policies and the management of freshwater ecosystems. Recent studies have

revealed the presence of cryptic or misclassified species within the genera *Barbodes*, *Rasbora*, and *Puntius*, which exhibit similar morphology but are genetically distinct. For instance, Bignotto *et al.* (2025) identified genetic contamination and misgrouping within the genus *Rhamdia*. These findings suggest that species complexes are prevalent in tropical river and lake systems, which often have complex biogeographic histories. Consequently, combining molecular and morphological methods is crucial for rectifying misclassifications and gaining a precise comprehending of freshwater biodiversity. A comprehensive understanding of the ecological requirements of native fish species—including habitat preferences, feeding patterns, and reproductive strategies—is critical for formulating effective management strategies. Consequently, investigations at the level of individual ecosystems are necessary as a foundational basis for broader-scale analyses (Gaglio *et al.,* 2024; Watson *et al.,* 2022). Integrating this study with both local and national policies is essential for maintaining the sustainability of the native fish resources found in Aneuk Laot Lake. One of the actions taken is through the Second Phase of the 15 Lakes Conservation Movement Program in Indonesia, which has designated Aneuk Laot Lake as one of the lakes requiring management. The findings of the study, which encompass precise identification of species, the identification of cryptic species potential, and the comprehension of genetic and morphological diversity among populations, provide important insights for creating management strategies that are adapted to the specific ecological circumstances of Aneuk Laot Lake. Currently, the increase in water temperature in the lake, caused by climate change, has a serious impact on fish habitat suitability, species distribution, and the overall dynamics of the lake ecosystem. These climate-induced changes pose significant challenges to the sustainability of fish populations and the ecological integrity of the lake ecosystem (Sharma *et al.,* 2019). In this context, ecosystem modeling is fundamental to improving fisheries management processes, as it facilitates more efficient tracking of changes within natural systems (Townsend *et al.,* 2019). Effective lake ecosystem management relies on a balanced relationship between human communities and natural resources, which necessitates the involvement of local communities in management activities (Lin *et al.,* 2014). The role of the communities around Aneuk Laot Lake in managing aquatic resources can foster the sustainability and conservation of fish resources. This method not only improves the feeling of ownership regarding local resources but also guarantees that policies are better suited to the local social and ecological contexts. Several management steps have been undertaken by the Sabang City Government, as outlined in planning documents based on the Mayor of Sabang's Decree No. 660/386/2019 regarding the Establishment of the Aneuk Laot Lake Management Working Group, which is integrated with the Regional Medium-Term Development Plan and the National, Aceh, and Sabang City Spatial Planning. Effective management of native fish in lakes requires an ecosystem-based approach tailored to the specific ecological and socio-economic context of each site (Johnson *et al.,* 2016). Such strategies include habitat restoration, such as the provision of spawning areas, as well as the implementation of water quality regulations and best management practices to reduce pollution and improve water clarity. Implementing restrictions on fishing practices, including catch size and quantity limits, is vital for preventing overexploitation and ensuring the long-term sustainability of native fish species. Furthermore, public education and awareness-raising efforts can promote responsible angling practices and strengthen stewardship for lake ecosystem conservation. Preventive measures, including strict quarantine protocols, are vital to avoid the introduction of potentially harmful non-native species (Kiruba-Sankar *et al.,* 2018).

CONCLUSION

This study underscores the importance of an integrative approach that combines morphological, morphometric, and molecular data for accurate identification of freshwater fish species. Based on observations of morphological and morphometric characters, the fish specimens collected from Aneuk Laot Lake were identified as *Barbodes sellifer*. This species exhibits distinct morphological traits, including a fusiform body shape, forked caudal fin, subterminal mouth, ctenoid scales, and a characteristic black blotch located between the anal and caudal fins. Body coloration can be observed in shades from silvery to brownish, accompanied by yellow to orange pigmentation on the dorsal,

anal, and caudal fins, consistent with the diagnostic characteristics of the Cyprinidae family. Conventional and truss morphometric analyses revealed substantial variation in body size, with a maximum total length of 12.52 cm and a standard length of 10.07 cm. The lowest variation was recorded in eye diameter and snout length. DNA barcoding using the mitochondrial COI gene successfully amplified all five fish samples from Aceh and showed strong concordance with *Barbodes sellifer*, based on both sequence similarity and phylogenetic reconstruction. The alignment of COI fragment length with earlier research further reinforces its credibility as a genetic marker for identifying species. Genetic distance analysis revealed low divergence between the study samples and *Barbodes sellifer*, reinforcing their identification as the same species. The analysis of genetics and morphology in *Barbodes sellifer* reveals a unique population structure with significant morphological diversity, although it is accompanied by a restricted level of genetic variability. Based on the low genetic variation and the presence of small or fragmented local populations, *B. sellifer* is potentially facing long-term ecological pressures. In this context, the appropriate conservation status to propose is Near Threatened (NT). This proposal is reinforced by the reduction in local population sizes due to the degradation of freshwater habitats, pollution, and uncontrolled fishing activities fishing pressures. Additionally, the low genetic diversity may reduce the species capacity to adapt to environmental changes, including climate change and anthropogenic disturbances. These findings highlight the importance of an integrative taxonomic approach—combining morphological characteristics, genetic data, and ecological context—as a crucial framework for uncovering cryptic diversity. Considering the widespread occurrence of intricate species in tropical freshwater ecosystems, this strategy is crucial for precise biodiversity recording and bolstering conservation initiative.

AUTHOR CONTRIBUTIONS

N. Fadli, as the corresponding author, designed the study and developed the main research concept, conducted molecular data analysis, and drafted the initial version of the manuscript. N. Nurfadillah, as the first author, was responsible for field sampling, morphological identification of specimens, preparation of morphometric tables and figures, and finalized the manuscript. Z. Jalil, performed statistical analyses, interpreted the research findings, and contributed to the development of the study methodology. N.A.M. Akib was involved in statistical analysis and result interpretation to support conservation recommendations based on phylogenetic data, as well as assisted in manuscript preparation. N.P. Anggraini, conducted DNA extraction, PCR amplification, and sequence alignment, and contributed to bioinformatics analysis and manuscript preparation.

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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.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
°C	Degrees Celsius
µL	Microliter
ACHa6	Code for Barbodes sp. specimen in genbank
B. sellifer	Barbodes sellifer
BIN	Barcode index number
BLAST	Basic local alignment search tool
BOLD	Barcode of life data system
bp	Base pair
CIA	Chloroform:isoamyl alcohol
COI	Cytochrome c oxidase subunit I
CTAB	Cetyltrimethylammonium bromide
cm	Centimeter
ddH_2O	Double-distilled water
DNA	Deoxyribonucleic acid
DO	Dissolved Oxygen
ED	Eye diameter
ETOH	Ethanol
F1	Forward primer 1
Fig.	Figure
K2P	Kimura 2-parameter
MEGA	Molecular evolutionary genetics analysis
ml	mililiters
mm	Milimeter
NCBI	National center for biotechnology information
NJ	Neighbor-joining
NT	Near Threatened
PCR	Polymerase chain reaction
pH	Potential of hydrogen
R1	Reverse primer 1
rpm	Revolutions per minute
SD	Standard deviation
SL	Standard length
SNL	Snout length
sp.	Species
UV	Ultraviolet
UVITEC	Ultraviolet transilluminator
ZEN	ZEISS efficient navigation

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ORIGINAL RESEARCH ARTICLE

Regulatory quality concerning carbon dioxide emissions in conjunction with the impact of fiscal decentralization

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ABSTRACT

BACKGROUND AND OBJECTIVES: Global carbon dioxide emissions have risen sharply in recent decades, sparking debate on the role of fiscal decentralization in environmental outcomes. Some argue that local autonomy fosters innovation and accountability, while others highlight risks of regulatory fragmentation and a "race to the bottom." This study aimed to explore the relationship between fiscal decentralization and carbon dioxide emissions, particularly highlighting the frequently overlooked role of regulatory quality, which has often been disregarded in past studies.

METHODS: A panel dataset of 73 countries (1990–2019) were analysed using indicators of fiscal decentralization (subnational expenditure, revenue, and vertical fiscal imbalance) from the International Monetary Fund's fiscal federalism database. Carbon dioxide emissions were measured per capita and per unit of gross domestic product to capture environmental burden and efficiency. According to the World Bank, regulatory quality was structured to act as a moderating variable. Control variables included gross domestic product per capita (and its quadratic form for the Environmental Kuznets Curve), trade openness, fossil fuel and renewable energy consumption, industrial share of gross domestic product, research and development expenditure, population growth and density, and natural resource rents. The estimation process employed panel fixed- and random-effects models, applying robust adjustments.

FINDINGS: Results demonstrate that fiscal decentralization, which includes autonomy in revenue and expenditure, is typically correlated with elevated carbon dioxide emissions per capita and per gross domestic product, exhibiting a stronger influence on per capita emissions. However, interaction with regulatory quality significantly reduces these impacts, confirming that strong institutions moderate negative environmental effects. Emissions have risen due to the increased use of fossil fuels, trade openness, and industrial activities, while factors such as population density and renewable energy consumption have contributed to their reduction. Vertical fiscal imbalance was insignificant, suggesting that emissions are driven more by subnational fiscal intensity than by dependence on central transfers.

CONCLUSION: Fiscal decentralization tends to increase carbon dioxide emissions, especially where institutions are weak. Regulatory quality acts as a crucial moderator, alleviating negative impacts without completely eliminating them. The findings highlight that fiscal decentralization alone does not ensure environmental efficiency; robust regulatory institutions and intergovernmental coordination are essential to align fiscal autonomy with environmental goals.

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Introduction

In recent decades, carbon dioxide (CO_2) emissions (one of the main greenhouse gases) have risen from 22,680.4 million metric tons in the early 1990s to 39,023.93 million metric tons in 2023, according to World Bank, (2024). Global warming has emerged as one of the most critical issues facing the world today, leading the global community to take notice of the environmental challenges tied to escalating CO_2 emissions (Boutabba, 2014; Siregar *et al.,* 2024; Adinugroho *et al.,* 2024). Among the measures to be adopted, some governments and academics believe that fiscal decentralization can be an effective way to mitigate CO_2 emissions. This occurs because the management of the environment by decentralized governments can be more specifically tailored and participatory, resulting in improved efficiency. However, another significant number of researchers find the opposite to be true: that fiscal decentralization, rather than promoting a reduction in emissions, creates conditions conducive to an increase, especially if there is no adequate institutional framework in place. It has been observed that local governments that are more in sync with the needs of their communities tend to establish more stringent environmental standards and policies. Consequently, local entities can execute mitigation initiatives (including land use, energy efficiency, and public transport) that resonate more closely with local circumstances, which boosts the effectiveness of these actions and fosters increased citizen engagement (Millimet, 2003; Chen and Chang, 2020; Levinson, 2003; Hering *et al.,* 2015). When citizens clearly demand respect for the environment and effective oversight mechanisms, governmental autonomy can translate into tangible environmental improvements (Dong *et al*., 2023; Xia *et al*., 2022). Local governments experiencing intense social demands enforce tougher fiscal policies, like green taxes and focused subsidies, thus overcoming the challenges posed by a centralized framework. According to Albrecht (2021), this constitutes an 'efficiency channel': the heterogeneity of preferences justifies fiscal decentralization to achieve greater environmental sensitivity and effectiveness. Thus, by reducing the gap between imposed and required standards, fiscal decentralization contributes to more effective environmental management. It is important to emphasize that the institutional framework can significantly influence both the intensity and direction of the impact of fiscal decentralization on the environment (Udeagha and Breitenbach, 2023; Udeagha and Ngepah, 2022). Greater fiscal autonomy for subnational governments, when not accompanied by institutional reforms and effective control and coordination mechanisms, can lead to a fragmentation of authority, eroding accountability and facilitating the capture of private interests. When fiscal decentralization grants discretion to subnational governments but there are deficiencies in coordination, accountability and environmental incentive systems, there are risks of capture by local elites, corruption, competition to attract highly polluting investments and systematic prioritisation of economic growth over environmental protection. This situation is commonly termed the 'race to the bottom'. Governments at the subnational level, having greater fiscal independence, vie to attract investments and enhance their local tax revenue, potentially leading to the easing of environmental regulations and, subsequently, an uptick CO_2 emission. In the absence of coordination mechanisms or minimum central standards, the relaxation of environmental policies or the lack of incentives to invest in clean and sustainable technologies perpetuates industrial practices that contribute significantly to an increase in total CO_2 emissions (Hong *et al.,* 2019; Becker, 2011; Tufail *et al.,* 2024, Xia *et al.,* 2021; Zhao *et al.,* 2023).

Vertical asymmetries and compensatory mechanisms

In addition to questioning the institutional framework, it is also possible to ask what type of fiscal decentralization is most environmentally favourable. The inconsistency between financial responsibilities and the genuine capacity to raise revenue is especially critical. If this imbalance is not adequately compensated for by institutional mechanisms (especially results-based transfers from central government), it may lead local authorities to prioritise short-term economic growth, often through activities with a high environmental impact, such as the expansion of polluting industries or the accelerated sale of land, over long-term investments in climate change mitigation and adaptation (Xia *et al*., 2021; Zhao *et al*., 2023; Xia *et al*., 2022). Additionally, there could be a decline in local environmental regulations due to insufficient resources for local governments to effectively implement or enforce these protections,

prioritizing more immediate and visible concerns instead (Zhao *et al*., 2023). In this regard, it is recommended that intergovernmental transfers take on an explicitly environmental character (conditional on the achievement of emission reduction or environmental quality improvement targets) and that the fiscal and institutional architecture promote coordination, transparency and the strengthening of evaluation mechanisms, especially in regions that are lagging. Moreover, subnational authorities should strive to minimize their dependence on alternative income sources that are highly polluting, such as swift urbanization or the uncontrolled growth of carbon-intensive industries.

Externalities and intergovernmental coordination

Multilevel institutional architecture is particularly relevant when analysing environmental problems, whose impacts transcend administrative boundaries and pose collective challenges. When subnational governments fail to take into account the welfare of surrounding jurisdictions, they may opt for more lenient environmental regulations than those mandated by a central government (Silva and Caplan, 1997), encouraging the transfer of polluting activities and increasing emissions not only locally but also in neighbouring regions (Xu and Li, 2022; Xia *et al*., 2021). Yang *et al*. (2020) identify this environmental free-rider effect. In the absence of coordination mechanisms, fiscal decentralization prompts local governments to be less willing to internalise the environmental costs of their actions, depending on the belief that other jurisdictions can, to some extent, absorb the negative externalities. This structure creates distorted incentives and hinders the optimal provision of environmental public goods. Given these externalities, the literature emphasises the need for intergovernmental coordination, whether vertical (between central and subnational governments) or horizontal (between jurisdictions of similar levels), to internalise externalities and ensure that fiscal autonomy does not undermine collective welfare. Xu and Li (2022) suggest the implementation of minimum national environmental standards, legal frameworks for information sharing and joint monitoring systems. These frameworks not only contribute to leveling the regulatory field but also discourage negative competitive actions. Another means for coordination identified by Dong *et al*. (2023) is the integration of green taxes at the local level and their harmonisation with national targets. The synergy of established fiscal decentralization with local environmental taxes and performance-based transfers is pivotal for attaining emission reduction goals in decentralised environments. Similarly, Yang *et al*. (2020) recommend incorporating CO_2 emission indicators into official performance evaluations as well as designing policies differentiated by region, given the different institutional capacities, levels of development and exposure to growth pressures faced by different provinces. Thus, it is evident that the repercussions of externalities and the opportunity for coordination depend on the developmental level, institutional quality, and economic framework of the regions. Xia *et al*. (2022) show that more developed regions tend to have better environmental outcomes under decentralised schemes, partly because they have a greater institutional capacity to coordinate and greater social demands for environmental regulations. Xu and Li (2022) warn that the most backward provinces, faced with budgetary pressure and lower technical capacities, may become hotspots for emissions displaced from other regions, a phenomenon that highlights the urgency of coordinated policies and corrective transfers to mitigate inequalities and avoid the geographical concentration of environmental risks.

Fiscal decentralization and environmental performance: the decisive role of regulatory quality

The relationship between fiscal decentralization and CO_2 emissions is undoubtedly complex. Several interrelated factors can affect it, including the regions' economic development status, the political and administrative organization, and the attributes of the tax system. The effects of fiscal decentralization on environmental conservation are not uniform and can vary widely depending on factors such as the level of economic development, the institutional structure and the availability of local resources. While it may be agreed that fiscal decentralization has a constructive environmental influence, institutional inequalities can prevent this positive outcome. The key may lie in institutions (Ahmed *et al*. 2020; Fredriksson and Millimet, 2002). As Rodden (2003) articulated, the results of fiscal decentralization are influenced by the institutional context in which it operates. Consequently, the prospective advantages of fiscal

decentralization are not solely based on the decentralization process, but on the institutional qualities that are present alongside it.. It is necessary to integrate institutions to understand how and under what circumstances fiscal decentralization can be beneficial, something that depends significantly on circumstances such as authority structures or the disposition of intergovernmental relations (Litvack *et al*., 1998; Hankla, 2009). This emphasises the importance of the quality of institutions in ensuring that fiscal decentralization leads to more efficient environmental management, lower CO_2 emissions and promoting the transition to renewable energies. It is believed that regulation is key to environmental protection and minimizing of pollution in a in a decentralised framework. Robust regulatory measures create a foundation for fiscal decentralization, encouraging sustainable innovation at the communities. The existence of a solid and coherent legal framework not only helps companies to engage in cleaner and more efficient practices but also empowers citizens to demand respect for and conservation of the natural environment. In addition, administrative regulation aids in establishing control and monitoring systems that enable the evaluation of adherence to environmental regulations and the implementation of corrective measures when required. In this regard, administrative regulation becomes an indispensable tool for coordinating actions between jurisdictions, the central government and communities, in order to preserve the environment and promote truly sustainable development. Nonetheless, in empirical terms, however, no study clearly utilizes a standard regulatory quality index to moderate the connection between fiscal decentralization and CO_2 emissions. Moreover, institutional moderation is often analysed alongside other proxies (environmental preferences, rigour indices and institutional efficiency) or the environmental outcome is viewed as a composite index not based exclusively on CO_2 emissions. Institutional or regulatory quality variables tend to appear only as controls or direct predictors in most studies. Regarding the direct effect of fiscal decentralization on CO_2 emissions, the studies reviewed show mixed results depending on the country, level of development and methodology applied. In developed countries, fiscal decentralization often results in lower CO_2 emissions, though the effects are not uniform across all levels (Wang *et al*., 2023). In South Africa, greater fiscal decentralization, expressed in greater spending autonomy and the authority to formulate local environmental policies, reduces emissions in both the short and long term (Udeagha and Breitenbach, 2023). Conversely, in China, the process of fiscal decentralization often contributes to rising CO_2 emissions, even though the nature of these relationships can be non-linear, influenced by the metrics and models that are used (Chen, 2022; Liu *et al*., 2023). In a multilateral forum for economic and diplomatic cooperation among emerging economies (BRICS) countries, greater fiscal decentralization is associated with higher CO_2 emissions (Udeagha and Ngepah, 2023). In the United States, fiscal decentralization shows a positive but statistically insignificant effect on carbon intensity in the agricultural sector (Ahmed *et al*., 2023). With regard to the analysis of an institutional factor, the literature recognizes two approaches: i) those that treat institutional or regulatory quality as a moderating factor in the relationship between fiscal decentralization and CO_2 emissions, and ii) those that include it as a direct predictor or control. Regarding the initial set of studies, none utilize a thorough and standardized regulatory quality index as an empirical moderating variable in the relationship between fiscal decentralization and CO_2 emissions. However, some use proxy or related measures. In the United States, Ahmed *et al*. (2023) used an environmental regulation index as a moderator. The effect of the interaction term (fiscal decentralization - environmental regulation) was negative but not significant at the national level and a significant effect was only detected in the western region of the country. In China, Liu *et al*. (2022) analysed the moderating effect of the government's environmental preferences on the relationship between fiscal decentralization and green development efficiency (a composite indicator that includes CO_2 but not exclusively). They identified a U-shaped relationship between both expenditure and revenue decentralization and green efficiency, noting that heightened environmental preferences strengthen the positive influence of fiscal decentralization. Another quasi-experimental study discovered that fiscal decentralization alone reduces the intensity of corporate emissions, with a greater reduction in Chinese counties with high institutional quality.

Nonetheless, the variable is neither clearly defined nor formally established as an empirical moderator (Yousaf *et al*., 2025). From a different viewpoint, another set of studies has considered institutional quality as a direct predictor of emissions, without specifically investigating its moderating influence. In developed countries, Wang *et al*. (2023) consider 'institutional efficiency' as a separate predictor, showing mitigating effects on emissions but no interaction with fiscal decentralization. In South Asia, Mahmood *et al*. (2022) use the World Bank's regulatory quality index, which shows a reducing effect on CO_2 emissions, but they did not model fiscal decentralization or interactions between the two variables. Studies focusing on China and resource-oriented economies have looked into proxies for regulation or institutional controls, but they have not explored their role as moderators (Chen, 2022; Liu *et al*., 2023; Udeagha and Ngepah, 2023; Udeagha and Breitenbach, 2023). In short, recent empirical literature confirms that both fiscal decentralization and institutional conditions play an important role in shaping CO_2 emissions. However, the formal interaction between fiscal decentralization and empirically measured regulatory quality has not yet been addressed. In contrast to earlier studies, this research clearly presents a standardized regulatory quality index as a moderating variable, thus offering unique empirical evidence on how institutions influence the connection between fiscal decentralization and CO_2 emissions. In this context, the objective was to contribute to a better understanding of the potential effects of fiscal decentralization on CO_2 emissions, with a particular focus on the role of regulatory quality in this relationship. In pursuit of this goal, a panel data set that includes various countries was employed to evaluate the direction and economic relevance of the potential influences. An empirical analysis was employed to reveal the extent to which fiscal decentralization has contributed to improving or worsening CO_2 emission levels in a large sample of countries over three decades, and the role of regulatory quality in moderating this relationship. The purpose of the present research is to analyze the link between fiscal decentralization and CO_2 emissions, particularly highlighting the moderating effect of regulatory quality. Drawing on a balanced panel of 73 countries (Afghanistan, Albania Armenia, Australia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Brazil, Bulgaria, Canada, Chile, China, Colombia, Costa Rica, Czech Republic, Denmark, El Salvador, Estonia, Finland, France, Georgia, Germany, Greece, Honduras, Hungary, Iceland, Indonesia, Iran, Ireland, Israel, Italy, Japan, Kazakhstan, Kenya, Kiribati, Korea, Kyrgyz Republic, Latvia, Lithuania, Luxembourg, Mauritius, México, Moldova, Mongolia, Myanmar, Netherlands, New Zealand, North Macedonia, Norway, Paraguay, Peru, Poland Portugal, Romania, Russian Federation, Serbia, Republic of Slovak Republic, Slovenia, South Africa, Spain, Sweden, Switzerland, Thailand, Tunisia, Turkey, Uganda, Ukraine, United Arab Emirates, United Kingdom, United States, and Uzbekistan) representing diverse levels of development, the research covers the period 1990–2019 to capture long-term trends and cross-national variation. Through the use of panel data modeling, this research aims to assess if fiscal decentralization leads to an enhancement or decline in environmental results, as well as to evaluate the degree to which regulatory institutions alleviate the adverse externalities linked to subnational fiscal independence. Accordingly, this study not only seeks to examine the relationship between fiscal decentralization, regulatory quality, and CO_2 emissions, but also to provide evidence that can guide public policy design. It aims to identify what types of institutional reforms—such as strengthening regulatory frameworks, implementing intergovernmental coordination mechanisms, or establishing minimum environmental standards, may enhance the positive effect of fiscal decentralization on the environment.

MATERIALS AND METHODS

To establish the role of fiscal decentralization in CO_2 emissions, an approach using panel data modelling for a sample of 73 countries at different levels of development is proposed, covering the years 1990 to 2019, using Eq. 1 (Grossman and Krueger, 1995; Udeagha and Breitenbach, 2023; Mahmood *et al*., 2022):

$$CO2_{it} = \beta_0 + \beta_1 GDPpC_{it} + \beta_2 GDPpC2_{it} + \beta_5 (DEC_{it} * QREG_{it}) + \beta_6 X_{it} + \varepsilon_{it} + v_{it} \quad (1)$$

Where, *i* refers to countries, *t* to years, β_0 is a constant, gross domestic product per capita (GDPpC)

is economic growth, DEC is a fiscal decentralization variable, QREG is the institutional variable of regulatory quality, X is a vector of control variables and ε is the error term.

The chosen sample countries were selected with the aim of maximizing geographical coverage, taking into account the availability of data. In other words, an effort was made to include as many countries as possible for which sufficient and comparable information is available so that the analysis is as broad and representative as possible within the limitations imposed by the data sources. The timeframe for this study was determined by noting that the rise of fiscal decentralization globally can be linked to the late 1980s, during a period of substantial political and economic reforms that aimed to improve state efficiency and deepen democratic practices. Countries in Latin America, Eastern Europe, Asia and Africa began to decentralise fiscal and management responsibilities to local and regional governments in response to structural reforms, democratic transitions and demands for greater local and regional autonomy. The dependent variable of pollution (CO_2) was measured in terms of the following two aspects. Per capita carbon dioxide emissions (CO_2pK) from the agricultural, energy, waste and industrial sectors were standardised to equivalent carbon dioxide values divided by population. To evaluate the effectiveness of fiscal decentralization in enhancing the environmental behavior of citizens or local public services, per capita CO_2 emissions were factored in. This is social or citizen environmental efficiency. Carbon intensity in gross domestic product (CO_2GDP) was also factored in. Annual carbon dioxide emissions from the agricultural, energy, waste and industrial sectors were divided by GDP in constant 2021 US dollars. This variable measures the amount of carbon dioxide emissions (kilograms of CO_2) per dollar of GDP generated, adjusted to constant 2015 prices. This is an essential metric for determining the environmental efficiency associated with the economic activities of a country or region. A high value indicates that the economy generates a greater amount of greenhouse gas emissions per unit of GDP, suggesting lower efficiency in terms of environmental sustainability. A low value means that the economy is more efficient in generating wealth with lower CO_2 emissions. By incorporating this variable, it was analyzed whether fiscal decentralization promotes a greener economic growth framework. This is referred to as the environmental efficiency of economic growth. Regarding the fiscal decentralization variable, the indicators of subnational expenditure and revenue over total public expenditure and revenue of the general government (FdExp / FdRev) and vertical fiscal imbalance (FdVimb) were used. These three indicators were chosen in an effort to comprehensively reflect the various aspects that might be part of a fiscal decentralization process. On the revenue side, its greater potential to generate incentives for greater fiscal responsibility stands out. Taxpayers identify a more evident relationship between the taxes they contribute and the environmental services they access, thereby enhancing accountability. Vertical imbalance reflects the difference between expenditure and own revenue and therefore considers the mismatch between the (de)centralisation of revenue and expenditure, which can create pressure on local jurisdictions to exploit their territory fiscally in the short term, thereby increasing CO_2 emissions. These metrics are sourced from the fiscal federalism database maintained by the International Monetary Fund (IMF, 2022). Regulatory quality (QREG) captures perceptions of the government's capacity to formulate and implement sound policies and regulations that enable and promote private sector development. The estimate reflects the country's score on the composite indicator expressed in terms of a standard normal distribution, which has been re-scaled to range from 1 to 6, guaranteeing that all variables are strictly positive and greater than 1. A quadratic function of the logarithm of GDP per capita is also included as a structural variable to represent the Kuznets environmental hypothesis (KEC). This hypothesis states that the relationship between economic growth and environmental degradation follows an "inverted U" curve since, in the early stages of economic development, growth is accompanied by an increase in pollution and environmental deterioration. Nonetheless, when per capita income surpasses a specific level, communities tend to focus on sustainability, allocate resources to cleaner technologies, and enforce more rigorous environmental regulations, which contributes to decreased pollution levels (Grossman and Krueger, 1995; Dasgupta *et al*., 2002; Stern, 2004).

Control variables include the following

Annual population growth (PopGrowth). This is calculated as the rate of change of the total population from one year to the next by considering births, deaths and net migration. Population growth can be linked to increased CO_2 emissions for a number of reasons. For instance, with the growth of the population, there is a corresponding rise in the demand for electricity, heating, transport, and consumer products, which in turn escalates the reliance on fossil fuels. Population growth drives urban expansion and infrastructure construction, which increases the use of cement, steel and other materials with high CO_2 emissions. Likewise, a larger population means greater exploitation of and destruction of natural resources, such as deforestation for agriculture or urbanisation, reducing the planet's capacity to absorb CO_2 (Dietz and Rosa, 1997; Martínez-Zarzoso, *et al*., 2006). Economic openness (Open). This is the sum of imports plus exports expressed as a percentage of GDP. It is generally accepted that more trade means more production and therefore more energy use, especially in industries that rely on fossil fuels. It also suggests an enhancement in international shipping (ships, planes, and lorries), which produces some considerable volume CO2 emissions (Sun *et al*., 2019; Tachie *et al*., 2020). Expenditure on research and development as a percentage of GDP (ResDevGDP). This measures the percentage of GDP that a country allocates to research and development (R+D). It includes expenditure on basic and applied research and technological development in sectors such as science, technology, health and industry. Investment levels in research and development can impact pollution in multiple mechanisms. Greater investment in R+D encourages innovation in renewable energies (solar, wind and hydrogen) and in more efficient industrial processes, reducing dependence on fossil fuels. Additionally, it fosters the advancement of carbon capture and storage technologies that contribute to the reduction of CO2 emissions in sectors with high pollution levels. On the other hand, technological growth driven by R+D can lead to greater production and consumption of goods, which can increase energy demand and, consequently, CO_2 emissions. A 'rebound effect' has been identified, where greater energy efficiency reduces costs and stimulates greater energy use (Fernández *et al*., 2018; Petrović and Lobanov, 2020). Revenue from natural resources expressed as a percentage of GDP (NatrecGDP). This indicates the fraction of GDP that is obtained through the extraction of natural resources including oil, natural gas, coal, minerals and forests. 'Rents' refers to the revenues generated by the exploitation of these resources after deducting the costs of extraction and production. The extraction and use of natural resources have a strong impact on CO_2 emissions, mainly due to the use of fossil fuels and environmental degradation. Nonetheless, if the income produced is allocated towards diversifying the economy and advancing renewable energy, the lasting environmental consequences can be mitigated (Adedoyin, 2019; Tufail *et al*., 2021). Population Density (PopDensity) measures the number of people per square kilometre. It is calculated by dividing the total population by the available land area (excluding bodies of water such as lakes and oceans). This assessment provides insight into the population's distribution and its potential consequences for infrastructure, the environment and the economy. Population density has a secondary effect on carbon dioxide emissions, influenced by elements such as urban growth, transportation systems, and energy utilization. Percentage of total energy consumption that comes from fossil fuels (FosEnergy), including coal, oil and natural gas. A high value means that most of the energy used in a country comes from fossil fuels. A low value indicates greater energy diversification, with a possible significant participation of renewable sources (hydroelectric, solar, wind, biomass etc.) Fossil fuel consumption stands as a major source of greenhouse gas emissions and atmospheric contaminants, influencing the environment negatively. Renewable energy consumption (RenoEner). This is the share of renewable energies in total final energy consumption. It includes hydroelectricity, solar energy (photovoltaic and thermal), wind energy, biomass and biogas (including wood, agricultural residues and biofuels) and geothermal energy. A significant value in this variable reflects a higher dependence on clean energy sources, while a lower value points to a greater reliance on fossil fuels. The use of renewable energy reduces environmental pollution, as it does not generate the same emissions and waste as fossil fuels. Industry (including construction) as a percentage of GDP (IndGDP). A high value signifies

that the industrial sector plays a major role in the economy, whereas a low value implies a stronger reliance on other sectors, like agriculture or services. Industry is one of the main sources of CO_2, methane and nitrogen oxides, and thus contributes to climate change. Variables exhibiting different temporal and cross-sectional coverage were processed with an unbalanced panel, employing all available information without the need for artificial imputations. This decision ensures the comparability of the results and is acknowledged as a limitation of the study. For this paper, the strategy was to estimate multiple models, varying the CO_2 and fiscal decentralization indicators available. This facilitated a more targeted and data-driven approach to the different pathways by which fiscal decentralization impacts environmental management. Restricted models were also conducted in which the variable of fiscal decentralization was introduced in terms of its interaction with regulatory quality. The hypothesis suggests that a higher degree of fiscal decentralization, evidenced through higher total subnational own revenues, should contribute to reducing CO_2 emissions, especially if fiscal decentralization is reinforced by higher regulatory quality. Given that the cross-section (countries) is integrated with the time series, panel data modeling was employed to examine this relationship. The challenge of estimating panel data lies in the need to explain heterogeneity, which may be given to a greater extent by individuals (countries) or by time. The estimation of panel data is based on the idea that the regression error (it) is the sum of the white noise residuals of the estimate (ε_{it}) and the component of heterogeneity not observed or not collected by the explanatory variables, which comes from the individual effects (α_{it}). This unobserved heterogeneity, as it is related to the independent variables, causes the estimators to be biased. This limitation can be resolved through two different estimation approaches: fixed effects on one side and random effects on the other. In the first case, the covariance between the unobserved heterogeneity and the explanatory variables is different from zero since it comes from individuals. Consequently, ordinary least squares were utilized, factoring in the differences of each variable, such as α_{it}, compared to their means, which leads to the term's disappears. In the second case, it is assumed that the covariance is zero, so heterogeneity is due to chance and not individual effects. It is estimated through generalised least squares (GLS) also as the difference between each variable with respect to its mean but multiplying this by a factor other than one. Selecting between fixed effects and random effects requires the Hausman test, whose null hypothesis implies the choice of a consistent model. Consequently, if the fixed-effect model is selected, it is crucial to confirm the homoscedasticity and the non-existence of autocorrelation in the regression residuals to ensure that the estimators are both unbiased and efficient. For this, the panel serial correlation test proposed by Wooldridge (2010) and Drukker (2003) was applied, with a null hypothesis of absence of autocorrelation, and the Wald statistic modified for fixed effect estimates in panel data proposed by Greene (2000), whose null hypothesis is the presence of homoscedasticity of the residuals. In cases where the null hypotheses should be rejected, it is important to alter the estimate through the application of panel-corrected standard errors (PCSE). This enables researchers to obtain robust results in the presence of autocorrelation and heteroscedasticity. This approach, in contrast to GLS for panels, adjusts standard errors while keeping the coefficient estimates unchanged. It uses robust corrections for standard errors and is more flexible, as it does not require the covariance structure of errors to be fully specified.

RESULTS AND DISCUSSION

As shown in Table 1, it is possible to state that in general the countries in the sample have a low level of middle-income distribution. GDP per capita (GDPpK) is just over US$18,000 at constant 2010 values. In general, their expenditure side is about 10 percentage points more decentralised than the revenue side, with subnational spending making up 28 percent of total general government expenditures. The level of participatory democracy can be improved since it is well below 50 points. The size of the state is around 35 percent (%) of public expenditure as a percentage of GDP, most of the population in the sample countries live in urban areas, the unemployment rate is around 8% of the economically active population and the average value of trade openness is just over 82% of GDP.

It is evident that the carbon intensity in relation to GDP and per capita demonstrates considerable

Table 1: Descriptive statistics. Dependent variables (CO_2pK and CO_2GDP), structural variable (GDP per capita), decentralization variables (subnational income and expenditure and vertical fiscal imbalance), regulatory quality and control variables (1990–2019)

Variable	N	Period		Maximum value	Minimum value
		Mean	Standard deviation (SD)		
CO_2pK	2160	6.6998	5.3889	32.1905	0.0388
CO_2GDP	2150	1.2366	1.3811	10.7354	0.0639
GDPpk	2190	18292.7	20714.5	113574.2	171.004
GDPpk2	2190	7.64e+08	1.55e+09	1.29e+10	29242.4
PopGrowth	2190	0.7781	1.3989	18.128	-8.101
Open	2077	82.368	42.9832	382.34	13.388
ResDevGDP	1404	1.191	1.0087	5.2156	0.015
NatrecGDP	2135	3.701	6.4915	44.596	0.000
PopDensity	2116	109.56	117.351	633.94	1.396
FosEnergy	1783	74.010	21.0111	100	0.000
Energy consumption	2190	22.122	21.2392	97.3	0.000
IndGDP	1993	27.834	7.8338	66.121	9.692
FdRev	1119	0.1797	0.1490	0.891	0.002
FdExp	1272	0.2818	0.1627	0.816	0.001
FdVimb	1309	0.4482	0.2428	0.96	-0.76
QREG	1530	4.0018	0.9409	5.581	1.1514

variability, with both showing extreme values. GDP per capita is also widely dispersed, reflecting structural differences between countries and between periods. Population growth rate, trade openness and population density are also variables with high SD, suggesting significant heterogeneity in the cases studied. The reliance on fossil fuels is considerable, in contrast to the relatively low average consumption of energy from renewable sources, which suggests that the energy matrix is still primarily controlled by non-renewable sources. The industrial sector's share of GDP is also significant. On average, there is a greater fiscal decentralization on the expenditure side than on the income side by about 10 percentage points, with subnational expenditure representing 28% of total general government expenditure. Finally, the regulatory quality (QREG), with a mean of 4.00 and deviation of 0.94, shows important differences in the institutional strength of the countries analysed.

Preliminarily, when analysing the Figs. (1 and 2) with average values of subnational revenue and expenditure, a clear positive association can be observed between fiscal decentralization and per capita CO_2 emissions. Nonetheless, once regulatory quality is factored in as an interacting element, this relationship is considerably diminished. This pattern suggests that the institutional framework, specifically the strength of regulatory mechanisms, plays a decisive moderating role in mitigating the environmental costs often associated with subnational fiscal autonomy. Table 2 presents the results of the regression models specified in Equation 1 for CO_2 emissions per capita according to subnational public expenditure and revenue, the vertical fiscal imbalance, the regulatory quality in interaction with these fiscal decentralization variables and, lastly, the control variables. The goodness of the models is is notable if one considers the significance of the variables and the overall estimates. Another notable point is that the Kuznets hypothesis seems validated, indicating that lower development levels lead to increase per capita CO2 emissions until a certain developmental threshold is crossed, after which the correlation becomes negative. Of the rest of the variables, economic openness, the consumption of energy from fossil fuels and the weight of the industrial sector in the economy seem to favour higher CO_2 emissions, although the latter variable only presents a significant

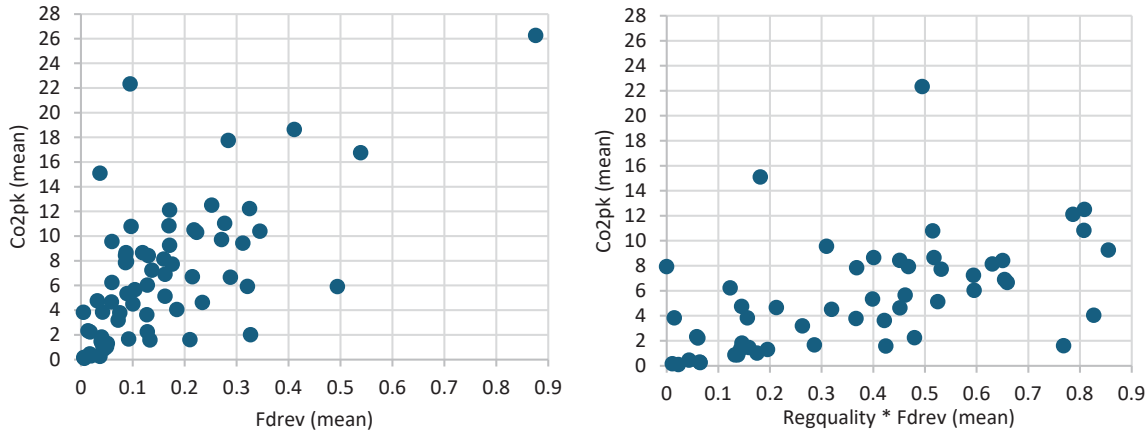

Fig. 1: Average CO_2 per capita vs. revenue decentralization, with and without interaction with regulatory quality

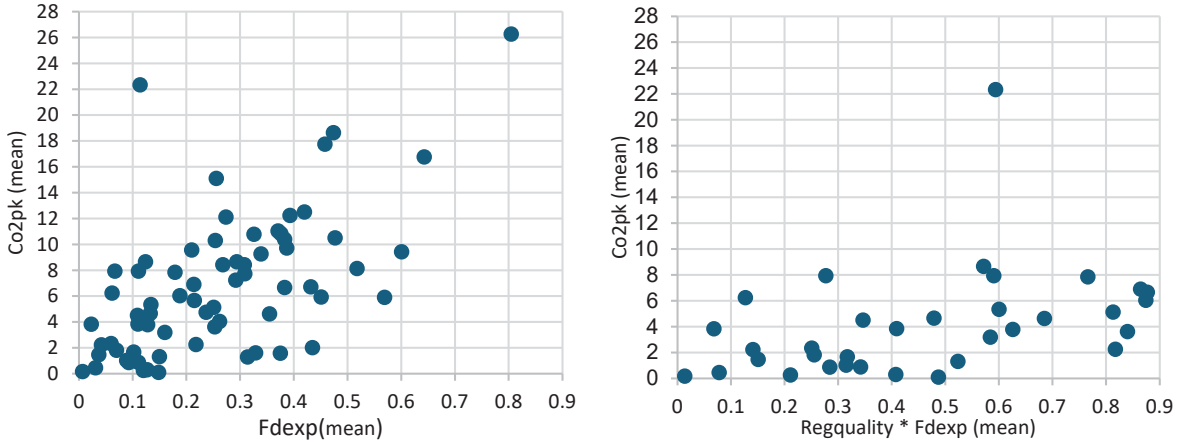

Fig. 2: Average CO_2 per capita vs. expenditure decentralization, with and without interaction with regulatory quality

coefficient in models 1 and 2 (when estimated with the subnational public revenue variable). Considering the coefficient values across all models, the energy consumption derived from fossil fuels is the variable that most significantly explains a country's emission levels. Those that appear significantly negative with respect to emissions are population density and energy consumption from renewable sources, the latter variable having a greater explanatory power if the value of its coefficient is adhered to. The rest of the control variables appear non-significant.

With respect to the decentralization variables, subnational public expenditure and revenue appear to be significant and positive coefficients. This indicates that fiscal decentralization, whether on the spending or income front, has not contributed to increased efficiency in environmental aspects, but has instead facilitated flexibility in the environmental conduct of citizens and local public services. Fiscal decentralization in regions with weak local institutions, scarce resources or low citizen pressure may result in ineffective or non-existent environmental services. This leads to highly polluting local practices (such as burning waste, using dirty fuels or unplanned urbanisation), thus increasing CO_2 per capita, even if economic activity is limited. Key services aimed at promoting sustainability, such as clean public transport, energy efficiency, forest management, and wetland conservation, face delays or are provided inefficiently. This contributes to car-based urban

Table 2: Robust correction estimates for CO_2 per capita, different decentralization indicators and control variables

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
GDPpk	0.0004***	0.0004***	0.0003***	0.0002***	0.0003***	0.0002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
GDPpk2	-5.20e-09***	-5.04e-0***	-2.27e-0***	-1.96e-0***	-2.12e-0***	-1.98e-0***
	(4.37e-10)	(4.32e-10)	(4.55e-10)	(4.71e-10)	(4.49e-10)	(4.46e-10)
PopGrowth	-0.049	-0.002	-0.077	-0.196*	-0.007	-0.106
	(0.991)	(0.097)	(0.107)	(0.107)	(0.110)	(0.107)
Open	0.008***	0.012***	0.013***	0.013***	0.011***	0.011***
	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)
ResDevGDP	-0.222	0.001	-0.291	0.162	-0.141	0.249
	(0.257)	(0.238)	(0.245)	(0.247)	(0.245)	(0.255)
NatrecGDP	0.014	0.020	0.023	0.028	0.035**	0.035**
	(0.013)	(0.014)	(0.015)	(0.018)	(0.016)	(0.018)
PopDensity	-0.011***	-0.012***	-0.011***	-0.011***	-0.010***	-0.010***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
FosEnergy	0.023*	-0.003	0.055***	0.029*	0.048***	0.026*
	(0.013)	(0.016)	(0.014)	(0.015)	(0.014)	(0.015)
EnergyConsumption	-0.074***	-0.098***	-0.070***	-0.084***	-0.067***	-0.081***
	(0.014)	(0.016)	(0.014)	(0.014)	(0.014)	(0.015)
IndGDP	0.057***	0.054***	0.008	0.030	0.014	0.033
	(0.015)	(0.016)	(0.019)	(0.021)	(0.020)	(0.022)
FdRev	4.054***	-	-	-	-	-
	(0.978)					
FdRev*QREG	-	1.430***	-	-	-	-
		(0.217)				
FdExp	-	-	2.796***	-	-	-
			(1.010)			
FdExp*QREG	-	-	-	0.703***	-	-
				(0.257)		
FdVimb	-	-	-	-	0.215	-
					(0.312)	
FdVimb*QREG	-	-	-	-	-	0.007
						(0.099)
Constant	-0.270	1.876	-0.750	0.950	0.114	1.591
	(1.484)	(1.710)	(1.518)	(1.612)	(1.482)	(1.562)
N (obs)	627	564	808	721	831	744
N (groups)	53	53	61	61	63	63
R2	0.776	0.824	0.746	0.777	0.726	0.763
Wald	6.0e+31***	3.5e+31***	6.0e+31***	35484.25***	5.9e+31***	5.7e+31***
Hausman	358.56***	107.57***	358.56***	168.86***	101.78***	118.42***

Note: Fixed effects were selected in all cases, but in the presence of autocorrelation and heteroscedasticity, robust estimation was chosen. Standard errors in parentheses. Significant up to 1% (***), between 1% and 5% (*) between 5% and 10% (*).

infrastructure, inefficient construction and local deforestation, all of which drive up emissions per capita. An examination of the coefficients reveals that fiscal decentralization in terms of revenue (autonomy to collect) exerts a more profound impact on CO_2 emissions than fiscal decentralization in terms of spending (responsibility in the use of resources). This implies that the enhancement of a local government's own resources results in greater CO_2 emissions, while the effect on expenditures is comparatively minor. This could be interpreted as evidence of how fiscal decentralization can give local governments, in the exercise of their fiscal autonomy, an important incentive to increase their tax bases, even if they are polluting, since these allow them to quickly expand their tax base (heavy industry, mining, construction or uncontrolled urbanisation). Conversely, a significant number of the newly generated environmental

costs remain unaccounted for within the system. In contrast, in the decentralization of spending, subnational governments use resources that usually come from the central government or are conditioned to specific goals (education, health or infrastructure). This curtails the discretionary expenditure of funds on polluting activities, permits the central government to enforce performance standards or targets (for instance, green investment), and facilitates the implementation of accountability mechanisms. In other words, coordination and external controls may be greater. An examination of the interaction between the levels of fiscal decentralization (subnational income and expenditure) and regulatory quality (Models 2 and 4) reveals that fiscal decentralization maintains its positive and significant sign—implying higher CO_2 emissions—although with much lower coefficient values. This appears to uncover a notable and somewhat anticipated trend: although fiscal decentralization has a positive and statistically significant impact on CO_2 emissions per capita, the magnitude of its coefficients is considerably diminished in environments with superior regulatory quality. This suggests that the quality of environmental regulatory institutions acts as a moderator that significantly mitigates the negative environmental impacts associated with subnational fiscal autonomy. In simpler terms, although fiscal decentralization typically leads to structural pressures that encourage carbon-heavy activities – like increasing tax bases through polluting sectors or deregulated competition across jurisdictions – these consequences are mitigated when local governments operate in institutional environments with clear rules, effective oversight mechanisms and sufficient technical capacity to implement and enforce environmental policies.

Table 3 includes models that take carbon intensity in GDP as a dependent variable (Models 7 to 12), which refers to the quantity of CO_2 emissions per dollar of Gross Domestic Product generated. Again, the goodness of the models is appreciable when consideration is given to the significance of the variables and of the estimates in general. The primary aspect that is noticeable is the discrepancies related to the estimates that utilized CO_2 per capita as the dependent variable. It is no longer social environmental efficiency but environmental efficiency of economic activity. For example, in this case, it is not possible to test the Kuznets hypothesis since the sign of the coefficients seems to indicate that, at low levels of development, pollution levels decrease, while as one advance in development, pollution levels increase. It appears that CO_2 emissions per unit of GDP are diminished by both population density and renewable energy usage, with the latter factor showing a greater influence when considering the values of the coefficients. On the other hand, trade openness, spending on research and development and the consumption of fossil fuels have a positive and significant relationship with CO_2 emissions. An examination of the coefficients reveals that expenditure on research and development as a percentage of GDP accounts for this increase to a greater extent, indicating a link between technological growth, higher energy demand, and consequently, increased CO_2 emissions. Concerning the variables of interest, the findings indicate that fiscal decentralization positively and significantly influences CO_2 emissions per capita; however, its effect on emissions per unit of GDP is considerably less pronounced. This difference can be interpreted from the conceptual distinction between the environmental intensity of economic growth (CO_2/GDP) and environmental burden per capita. The initial indicator indicates the efficiency of an economy in converting inputs into added value in relation to its emissions, whereas the second one evaluates the environmental consequences allocated per person, which is notably affected by the territorial, population and sectoral dynamics induced by decentralization. From an incentive perspective, fiscal decentralization, whether on the revenue or expenditure side, may foster greater interjurisdictional competition to attract investment. A significant portion of this investment is carbon-heavy, with short-term goals frequently taking precedence over environmental public benefits. Nonetheless, this trend does not consistently result in a considerable decline in overall environmental efficiency, particularly when GDP growth is associated with increasing emissions. Hence, the effect on CO_2/GDP may be more attenuated. Conversely, the effect on CO_2 emissions per person is more pronounced, as it indicates the local externalization of environmental harm and its allocation among the population. Again, if the interaction between the levels of fiscal decentralization (income and subnational expenditure) and the levels of regulatory quality

Table 3: Robust correction estimates for CO_2 per GDP, different decentralization indicators and control variables

Variable	Model 7	Model 8	Model 9	(Model 10	Model 11	Model 12
GDPpk	-0.00006***	-0.00007***	-0.00006***	-0.00006***	-0.00005***	-0.00005***
	(5.81e-06)	(6.48e-06)	(4.79e-06)	(4.83e-06)	(4.01e-06)	(4.74e-06)
GDPpk2	5.95e-10***	6.12e-1***	5.52e-1***	4.92e-1***	4.01e-1***	3.93e-1***
	(7.18e-11)	(7.71e-11)	(4.77e-11)	(4.70e-11)	(4.08e-11)	(4.77e-11)
PopGrowth	0.014	0.054*	-0.067***	-0.063***	0.005	0.037*
	(0.024)	(0.029)	(0.018)	(0.018)	(0.016)	(0.022)
Open	0.002***	0.003***	-0.0001	0.00007	0.0009*	0.001***
	(0.000)	(0.000)	(0.000)	(0.0005)	(0.000)	(0.000)
ResDevGDP	0.102***	0.1201***	0.101***	0.084***	0.078***	0.082***
	(0.032)	(0.033)	(0.031)	(0.031)	(0.022)	(0.027)
NatrecGDP	0.014	0.013	-0.015***	-0.009***	0.010	0.011
	(0.008)	(0.011)	(0.003)	(0.003)	(0.007)	(0.010)
PopDensity	-0.002***	-0.002***	-0.0007	-0.0009*	-0.001***	-0.001***
	(0.0002)	(0.0003)	(0.0005)	(0.0005)	(0.0002)	(0.0002)
FosEnergy	0.004**	0.004**	0.007***	0.005***	0.003**	0.004***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
EnergyConsumption	-0.010***	-0.014***	-0.002	-0.004**	-0.007***	-0.009***
	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
IndGDP	-0.011	-0.017**	0.004	0.004	-0.002	-0.009
	(0.007)	(0.0090)	(0.003)	(0.003)	(0.005)	(0.006)
FdRev	0.542**		-			
	(0.265)					
FdRev*QREG		0.086	-			
		(0.061)				
FdExp			0.763***			
			(0.159)			
FdExp*QREG			-	0.086***		
				(0.034)		
FdVimb			-		-0.206	
					(0.149)	
FdVimb*QREG						-0.070
						(0.043)
Constant	1.908***	2.127	1.099***	1.365***	1.837***	1.962***
	(0.270)	(0.281)	(0.263)	(0.255)	(0.224)	(0.247)
N (obs)	627	564	808	721	831	744
N (groups)	53	53	61	61	63	63
R2	0.642	0.629	0.411	0.436	0.602	0.602
Wald	9.0e+07***	2.5e+3**	2.4e+0***	3.2e+3***	7.4e+3***	3.5e+3***
Hausman	126.49***	116.13***	-398.13	-6.44	41.09***	102.50***

Note: Fixed effects were selected in models 7, 8, 11 and 12, but in the presence of autocorrelation and heteroscedasticity, robust estimation was chosen. Models 9 and 10 have been estimated with random effects. Standard errors in parentheses. Significant up to 1% (***), between 1% and 5% (*) between 5% and 10% (*).

(Models 8 and 10) is analysed, decentralization in terms of income is observed to lose its significance, whereas decentralization in terms of expenditure retains significance, though with a considerably lower coefficient value. This reinforces the expected pattern: even though decentralization has a positive and statistically significant effect on CO_2 emissions per GDP, the importance of its coefficients either loses significance or is markedly decreased in settings with enhanced regulatory quality. This presents further evidence (now in the case of environmental economic efficiency) of how the quality of regulatory institutions acts as a moderator that mitigates the negative environmental impacts associated with subnational fiscal autonomy. In other terms, fiscal decentralization seems to generate structural pressures that encourage carbon-heavy activities, for instance, via unregulated competition between

authorities. Yet negative impacts tend to diminish precisely when local governments must act within strong institutional frameworks, with well-defined rules and effective control systems. Finally, the vertical fiscal imbalance variable appears to be non-significant with respect to CO_2 emissions per capita and per GDP (Models 5, 6, 11 and 12). This may imply that the financial dependence of subnational governments does not appear to directly impact emissions levels. The intensity of fiscal activity at the subnational levels (what they spend and collect), rather than their dependence on the central government, is what is associated with higher levels of polluting emissions.

CONCLUSION

Empirical evidence shows that fiscal decentralization is positively and significantly related to higher CO_2 emissions per capita and per unit of GDP, although in the latter case to a lesser extent. Considering regulatory quality, the influence of fiscal decentralization on emissions diminishes considerably, implying that effective environmental institutions, particularly those focused on regulation, alleviate the detrimental environmental consequences of fiscal decentralization. Variables such as population density and the use of renewable energies help to reduce carbon intensity, while trade openness, fossil fuel consumption and investment in R+D increase it. Conversely, the vertical fiscal imbalance is not substantial in any model, indicating that it is not the financial reliance on the central government that influences emission levels, but rather the degree of subnational fiscal activity. These results seem to support the literature that identifies fiscal decentralization as a framework of conditions conducive to the increase in CO_2 emissions, especially in the absence of an adequate institutional framework. Instead of realising the channels of efficiency that were expected with fiscal decentralization, such as greater sensitivity to local conditions or the strengthening of accountability, jurisdictions have important incentives to stimulate economic growth based on the exploitation of their local resources. Managers at the local level, driven by short-term electoral ambitions, work to attract investments and grow their local tax base, often compromising environmental standards, as evidenced by an uptick in CO_2 emissions. The realisation of the channels of efficiency that are expected of decentralising processes is only possible if the channels are presented in an ideal institutional framework. This concept is particularly important concerning to the environment. Certainly, in many countries, the fragmentation of authority, instead of promoting citizen participation, transparency and a better knowledge and adaptation of local environmental conditions, has eroded accountability and facilitated the capture of private interests. The outcome reflected a strategic commitment by local authorities to carbon-heavy economic activities, focused on maximizing immediate revenue, even at the expense of future environmental health. It is important to remember that fiscal decentralization, especially in developing countries, has been implemented without decision-makers knowing that many of the expected incentives would not be realised under certain prevailing conditions (limited capacity for the movement of people but not of capital, reduced levels of public goods, low tax burdens, poor democratic performance, weak local administrative structures etc.) Instead of promoting environmental efficiency mechanisms, less developed regions or regions with weaker institutions would become a 'refuge' for polluting activities, with the ample possibility of externalising their negative environmental costs. The findings regarding the interplay between fiscal decentralization and regulatory quality indicate that decentralization is crucial for fostering sustainable innovation, enhancing environmental oversight, and empowering the community. In environmental terms, a structuring framework is needed to guide the behaviour of subnational governments and reduce the risks of distortion. In decentralised contexts, strong and consistent regulation allows for the establishment of minimum standards, ensures transparency in policy formulation and implementation and promotes accountability mechanisms that limit local capture or the inefficient use of fiscal autonomy. In addition, regulatory quality facilitates coordination between levels of government, harmonises incentives and reduces institutional asymmetries, which improves the allocation of expenditure and strengthens the provision of public goods, such as environmental goods. The evidence points to regulatory quality being more than just a broad institutional requirement; it encompasses a range of tangible mechanisms

that can reduce the environmental risks of fiscal decentralization. Stronger regulation can translate into minimum national standards, intergovernmental coordination schemes, and improved accountability, all of which are critical to ensuring that subnational fiscal autonomy does not undermine sustainability. In this way, the empirical evidence indicating that greater institutional efficiency mitigates CO_2 emissions in decentralised environments is expanded. Ultimately, there is no indication that vertical fiscal asymmetries lead to increased CO_2 emissions. As indicated, these may come from the expansion of their fiscal capacities but not from fiscal financial dependence, which may be adequately covered by intergovernmental transfer systems in most countries. The conclusion reached indicates that fiscal decentralization typically results in higher CO_2 emissions, given that local governments, in their independent decision-making, tend to favor short-term economic development rather than sustainability initiatives. Regulatory quality moderates these negative effects without making them environmentally positive. However, regulatory quality remains important for fiscal decentralization to achieve environmental efficiency objectives.

AUTHOR CONTRIBUTIONS

D. Pinilla-Rodríguez, the corresponding author, led the conceptualization and methodology of the study, conducted the formal analysis, curated the data, and prepared all figures. He was primarily responsible for drafting the original manuscript, revising and editing its content, and supervising the overall research process. P. Hernández-Medina contributed to data curation, participated in the validation of results, and collaborated in the review and editing of the manuscript.

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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.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
BRICS	It is a multilateral forum for economic and diplomatic cooperation among emerging economies, currently encompassing eleven member countries: Brazil, Russia, India, China, South Africa, Egypt, Ethiopia, Iran, Saudi Arabia, the United Arab Emirates, and Indonesia
CO_2	Carbon dioxide
CO_2GDP	Carbon intensity in gross domestic product

FdExp	Subnational expenditure as a percentage of total general government expenditure
FdRev	Subnational revenue as a percentage of total general government revenue
FdVimb	Vertical fiscal imbalance
FE	fixed effects
GDP	Gross domestic product
GDPpC	Gross domestic product per capita
GLS	Generalised least squares
Hausman	Hausman test for fixed or random effects selection
IndGDP	Industry (including construction) as a percentage of GDP
KEC	Kuznets environmental hypothesis
NatrecGDP	Natural resource rents as a percentage of GDP
Open	Economic openness
PCSE	Panel-corrected standard errors
PopDensity	Population density
PopGrowth	Annual population growth
QREG	Regulatory quality
R+D	Research and development
R2 between	Proportion that the model is able to explain of the variability of the dependent variable across countries.
R2 overall	Proportion that the model can explain of the variability of the dependent variable
R2 within	Proportion of the variability of the dependent variable over time that the model is able to explain
RE	Random effects
RenoEner	Renewable energy consumption
ResDevGDP	Research and development expenditure as a percentage of GDP
SD	Standard deviation
US$	U.S. dollars
Wald chi2	Goodness-of-fit test (overall significance of explicative variables)

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ORIGINAL RESEARCH PAPER

Hybrid sediment microbial fuel cells utilizing Spirulina platensis for concurrent energy harvesting, pollutant removal, and algal biomass production

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ABSTRACT

BACKGROUND AND OBJECTIVES: Oxygen availability in the cathode chamber is crucial for electricity generation in sediment microbial fuel cells. Microalgae, such as Spirulina platensis, can enhance dissolved oxygen through photosynthesis. Integrating microalgae within sediment microbial fuel cells increases energy output, enhances the removal of pollutants, and aids in . The study objectives were to assess electricity generation, pollutant removal, cathode biofilm formation, and Spirulina platensis growth in an sediment microbial fuel cells system.

METHODS: Sediment microbial fuel cells were created by combining sediment with the overlying water taken from a polluted artificial lake. Spirulina platensis was obtained from a local aquaculture center and added in four volumetric ratios to lake water (0/2000, 400/1600, 1200/800, and 1600/400 milliliters) as catholyte. The reactors operated in closed-circuit mode for 28 days. The parameters analyzed consisted of current and power density, sediment microbial fuel cell-based biofilm formation, and algal biomass and chlorophyll content.

FINDINGS: Achieving the highest power density of 83.61 milliwatts per square meter and a current density of 48.43 milliamperes per square meter, the 1600 to 400 milliliters configuration is approximately 43 percent higher than the control. The 1200 to 800 milliliters setup exhibited the best pollutant removal performance. The 1200 to 800 milliliters showed, chemical oxygen demand on overlying water was reduced from 139.44 ± 6.97 milligrams per liter to 69.42 ± 8.37 milligrams per liter ($p = 0.0025$), ammonia nitrogen from 1.72 ± 0.27 milligrams per liter to 0.06 ± 0.03 milligrams per liter. The 1200/800 condition achieved the highest biomass levels during day 21 with 0.96 grams per liter. Scanning electron microscopy revealed dense biofilm and filamentous microalgae structures on the cathode, facilitating oxygen production and electron transfer.

CONCLUSION: Spirulina platensis significantly improves sediment microbial fuel cells performance through oxygen generation, pollutant removal, and biomass growth. The 1600/400 ratio is optimal for electricity generation, while 1200/800 is preferable for bioremediation and microalgae productivity. Further studies ought to emphasize sustainable performance and nutrient management.

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INTRODUCTION

Lake ecosystems are increasingly threatened by high pollutant loads such as organic matter, nutrients, heavy metals, microplastics, and pesticides (Soeprobowti et al., 2023; Wulandari et al., 2024; Utari et al., 2024). When these surpass the lake's capacity to hold, pollutants build up in the sediments and may re-enter the water column, compromising water quality (Fitriani et al., 2025). Traditional sediment remediation like dredging is costly and time-consuming. As another option, sediment microbial fuel cells (SMFCs) serve as a sustainable technology that addresses contaminated sediments and generates electricity in situ (Kim et al., 2020; Jabbar et al., 2023). SMFCs do not require expensive electrode catalysts, membranes, or aerator systems, which further reduces initial costs. (Neethu and Ghangrekar, 2017). In SMFCs, exoelectrogenic bacteria oxidize organic matter at the anode in anaerobic sediment and transfer electrons to the cathode in oxygenated water (Song et al., 2020). Significant performance improvements have been made by modifying electrodes, redesigning anodes, and enhancing catalysts (Abbas et al., 2019; Mohd Noor et al., 2024). One promising approach is using photosynthetic microalgae to enrich oxygen at the cathode, enhancing electron transfer and electricity generation (Ucar et al., 2017; Hadiyanto et al., 2023). Microalgae contribute to nutrient elimination and offer biomass for the generation of biofuels. Their chlorophyll content reflects photosynthetic activity, which correlates with power output (Chojnacka et al., 2018; Tay et al., 2024). Among the options, *Spirulina platensis* has exhibited enhanced performance relative to *Chlorella sp*., resulting in increased power density and biomass (Hadiyanto et al., 2020; Kakarla et al., 2017). *S. platensis* is commonly found in tropical regions, including Indonesia, the location of this study. While previous research often used constant illumination, limited studies have addressed the effect of natural light/dark cycles on SMFC performance in tropical environments (Misali et al., 2024; Anandapadmanaban et al., 2025). *S. Platensis* is sensitive to high levels of light, which can negatively affect its photosynthetic system. However, occasional or intermittent exposure to light can mitigate the harmful effects of light-induced stress (Maali et al., 2021). According to Richter (2016), a 12-hour light/12-hour dark cycle closely reflects tropical conditions. This condition will allow this study to more closely reflect the environmental conditions for future application. This study investigates the effects of *S. platensis* on electricity generation, nutrient removal such as chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), phosphate phosphorus (PO_4-P), biofilm formation, and growth dynamics under tropical light/dark conditions using polluted lake sediment and water. This study aimed to assess electricity generation, pollutant removal, cathode biofilm formation, and *S. platensis* growth in an SMFC system. This study has been contacted in Surabaya City in East Java, Indonesia in 2023.

MATERIALS AND METHODS

Water and sediment samples were collected from an euthropical lake at Boezem Morokrembangan of Surabaya City in East Java, Indonesia. The Bozem Morokrembangan artificial lake was placed at 7°13'55" south (S) 112°43'03" east (E). The water samples was collected with water sampler. Meanwhile, the sediment samples were collected at a depth of 0-20 centimeters (cm) with ponar grab.

Cultivation of Spirulina platensis

S. platensis monocultures were bought from the Jepara Brackishwater Aquaculture Development Center in Central Java, Indonesia. The batch culture of this algae was conducted at the laboratory. Cultivation was conducted under 3200 ± 100 lux fluorescent light (12 hours light/12 hours dark). The light exposure was using Philips Life-max tubular light type D (TLD) 36W/54-765 lamps. The procedure took place at room temperature while ensuring continuous aeration. Walne fertilizer 1 mililiter per liter (mL/L) was added every five days.

SMFC construction and operation

In the laboratory condition, five liters of total volume low-density polyethylene (LDPE) container was used as SMFC reactors. The construction involved two liters of collected polluted sediment serving as the anolyte and two liters of overlying water functioning as the cathode. The cathodic was the sterilized water from Boezem Morokrembangan, autoclaved at 121 degree Celsius (°C) for 20 minutes. Prior to the introduction of the *S. platensis* monoculture, the overlying water underwent autoclaving to eradicate microorganisms. The anode and cathode electrodes, made of 9 × 9

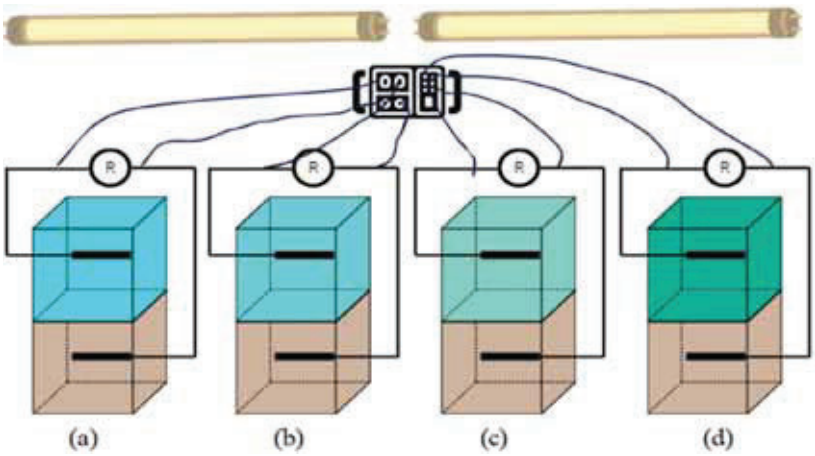

Fig. 1: Schematic diagram of SMFC reactors with *S. platensis*/water ratio (a) 0/2000; (b) 400/1600; (c) 1200/800; (d) 1600/400

cm graphite felt, were heated in a furnace at 450°C for 30 minutes. The anode, serving as the electrode, was placed at a depth of 4 cm beneath the surface sediment, while the cathode was positioned in the center of the overlying water. The anode and cathode were connected with titanium wire and 1000 ohm (Ω) of resistors and data logger (Oktavitri et al., 2021). Four SMFC reactors were prepared for experimental treatment SMFC with ratio between *S. platensis* and autoclaved water from artificial lake 0/2000; 400/1600; 1200/800; and 1600/400. SMFCs were operated for 28 days under a close circuit mode (Fig. 1). During SMFC operation, the decrease in overlying water height was compensated by adding water based on the original *S. platensis* composition ratios: 0/2000, 400/1600, 1200/800, and 1600/400.

Electricity generation analysis

The electricity production was recorded every 5 minutes with Hioki LR8431-20 Hi-Logger. The polarization was conducted at 28 days with various resistors from 0, 56000 to 10 ohms. The anodic and cathodic polarization was performed using a silver/silver chloride electrode (Ag/AgCl) as the reference electrode. The power density and current density were calculated, using Eqs. 1 and 2 (Misali et al., 2024):

$$P = \frac{V^2}{1000.R.A} \quad (1)$$

$$i = \frac{V}{1000.R.A} \quad (2)$$

Where:
P = power density (mW/mA)
V = voltage (V)
i = current density (mA/m^2)
A= area of electrode (m^2)
R= external resistance (ohm)

The ohmic polarization was the linear shape from current density vs voltage graph. The slope of the linear line was the value for calculation of the ohmic resistance. The ohmic resistance (RΩ) was calculated by the slope of the voltage-current curve, using Eq. 3 (Fuller and Harb, 2018):

Moreover, microalgae biomass serves as a valuable feedstock for biodiesel production, offering a sustainable alternative energy source.

$$\text{Slope} = \frac{\Delta V}{\Delta i} = \Omega m^2 \quad (3)$$

Scanning electron microscopy (SEM) analysis

The examination of the surface morphology and structural attributes of biofilms on the cathode functioning as an electrode was conducted through SEM. The SEM with Thermo Fisher Scientific Phenom P-Series (Netherland manufactured) provides high-resolution images of microbial attachment and biofilm architecture. SEM analysis was performed with the test samples dry. The cathode samples were prepared with a size of 1 cm x 1 cm and then coated to make the samples more conductive and produce sharp images before analysis. Biofilm coverage area

Table 1: Initial concentration

Parameter	Unit	Value	
		Sediment	Water
pH	-	9.81 ± 0.39	8.6±0.01
Temperature	°C	26.33 ± 0.06	26.37± 0.06
ORP	mV	-153.33 ± 3.51	296.33 ± 3.51
LOI	%	6.44 ± 0.71	-
COD	mg/L	555.00 ± 27.75	139.44 ± 6.97
NH_3-N	mg/L	86.62 ± 0.48	1.72 ± 0.27
PO_4-P	mg/L	2.33 ± 0.20	4.00 ± 0.24

was analyzed using open source software, ImageJ from U. S. National Institutes of Health, Bethesda, Maryland, USA (Mountcastle *et al.*, 2021). Manually selecting the Region of Interest (ROI) ensured that only the target areas were included. Images underwent conversion to binary using thresholding to differentiate the biofilm from the background. The scale bar was used to set the image scale in micrometers. Analyze Particles tools was applied to measure area, count, and shape of features. Non-biofilm areas were quantified, and data were exported for further analysis.

Chemical analysis parameter

The potential of hydrogen (pH), oxidation-reduction potential (ORP), and temperature of sediment and over-lying water with Thermo scientific Eutech pH 6+. Environmental parameters were analyzed in triplicate. Prior to conducting the nutrient and organic matter analysis, the gathered artificial lake water was filtered through Whatman glass fiber grade C (GF/C) with a diameter of 47 mm to eliminate suspended particles. The pore water was extracted from the collected sediment sample by centrifuging (Eppendorf centrifuge 5702) at 3800 rpm for 10 min. COD, PO_4-P, and NH_3-N concentrations of the overlying water and sediment pore water were analyzed based on standard methods. Analysis of PO_4-P and NH_3-N concentrations was determined using a spectrophotometer based on Standard Methods 4500-NH_3-N and Standard Methods 4500-P (Baird *et al.*, 2017). In addition, for COD analysis using the standard method for the examination of water and wastewater, Standard Methods 5220-D (Baird *et al.*, 2017). The Loss on Ignition (LoI) was analyzed for estimating the organic matter content in the sediment (Bensharada *et al., 2022*). Table 1 presents the initial condition of sediment and overlying water. The environmental parameters underwent statistical evaluation via the Kruskal-Wallis test, with subsequent post-hoc comparisons performed using Dunn's test, facilitated by the rstatix package in R.

Biomass and chlorophyll analysis

The Whatman GF/C filter papers (47 mm diameter) were pre-dried at 105°C and weighed as (W_A). Later, a 25 mL (v) aliquot of the laboratory-cultured microalgal suspension was filtered through these pre-dried GF/C filter papers. Subsequently, 25 mL of fresh distilled water was used for rinsing to eliminate any insoluble salts from the culture medium. The filter paper containing the biomass was then dried in an oven at 105°C. Subsequently, the filter paper was placed in a desiccator to cool and dry then reweighed (W_B). The biomass was calculated according to Eq. 4 modified (González-Hourcade *et al.*, 2022):

$$\text{Biomass}\left(\text{g}/\text{L}\right)=\frac{\left(\text{W}_\text{A}-\text{W}_\text{B}\right)}{\text{v}} \quad (4)$$

Chlorophyll content was determined by collecting samples and resuspending them in acetone. Using centrifugation, the supernatant that contains chlorophyll was extracted. Absorbance measurements of the supernatant were conducted using a UV-VIS spectrophotometer at wavelengths of 663 nm (A663) and 645 nm (A645). The calculations for chlorophyll a, chlorophyll b, and total chlorophyll concentrations were performed, using Eqs. 5, 6, and 7 (Abdul-Adel *et al.*, 2019).

Chlorophyll a (mg/L) = (12.7 x A663)-(2.698-A645) (5)

Chlorophyll b (mg/L) = (22.9 x A645)-(4.68-A663) (6)

Total Chlorophyll (mg/L) = Chlorophyll a (mg/

L)+Chlorophyll b (mg/L) (7)

RESULTS AND DISCUSSION

Electricity production

The introduction of *S. platensis* significantly influenced current density fluctuations over a 30-day operational period (Fig. 2). Current density ranged from 8.77 to 48.43 milliampere per square metre (mA/m²) across various microalgae-to-overlying water volume ratios (V/V): 0/2000, 400/1600, 1200/800, and 1600/400. The reactor with a 1200/800 ratio exhibited a high current density during the initial 5 days of operation, followed by a gradual decline. All setups stabilized in current density after 10 days. The 1600/400 ratio showing the highest value (48.43 mA/m²), while the 0/2000, 400/1600, and 1200/800 ratios reached 33.32, 34.70, and 34.09 mA/m², respectively. In contrast, the SMFC without *S. platensis* (0/2000) generated a maximum current density of only 33.32 mA/m². This advancement illustrates the successful degradation of organic material by anode microorganisms that are well-adapted, along with the cooperative relationship between bacteria and microalgae in the cathodic compartment. The electricity generation data indicate that the addition of *S. platensis*. significantly enhances electricity production in SMFCs (Fig. 2). Carbon dioxide (CO_2) produced during microbial metabolism in the anode compartment is consumed by microalgal cells in the cathodic compartment. Oxygen, created via the photosynthetic activity of microalgae, functions as the ultimate electron acceptor. Bacteria can utilize this for aerobic respiration, thus impacting the system's redox conditions. The production of oxygen can full fill the requirement of oxygen on cathode for redox reaction (Khan *et al.*, 2021; Rajamanickam and Selvasembian, 2024).

Microalgae-based cathodes in SMFCs enhance performance by promoting in situ oxygen (O_2) production. In the anode, bacteria oxidize organics, releasing CO_2, H^+, and electrons. *S. platensis* in the cathode uses light to photosynthesize, generating oxygen and removing CO_2 and nutrients without extra energy input (Ezziat *et al.*, 2019). According to the study conducted by Abazarian *et al.* (2020), it was indicated that SMFCs utilizing algae exhibit elevated oxygen levels, resulting in increased power output. In addition, this study applied a light/dark cycle, which supports current generation during light periods through oxygen production from photosynthetic activity (Misali *et al.*, 2024). Moreover, a study conducted by Sharma *et al.* (2024) indicated that the ongoing proliferation of microalgae in the cathode region can elevate dissolved oxygen concentrations,

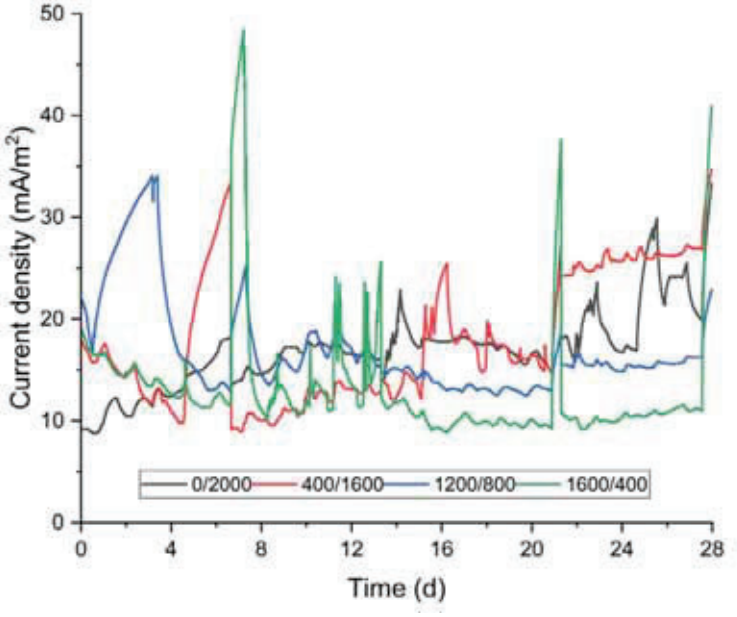

Fig. 2: The current density output of SMFCs with and without *S. platensis*

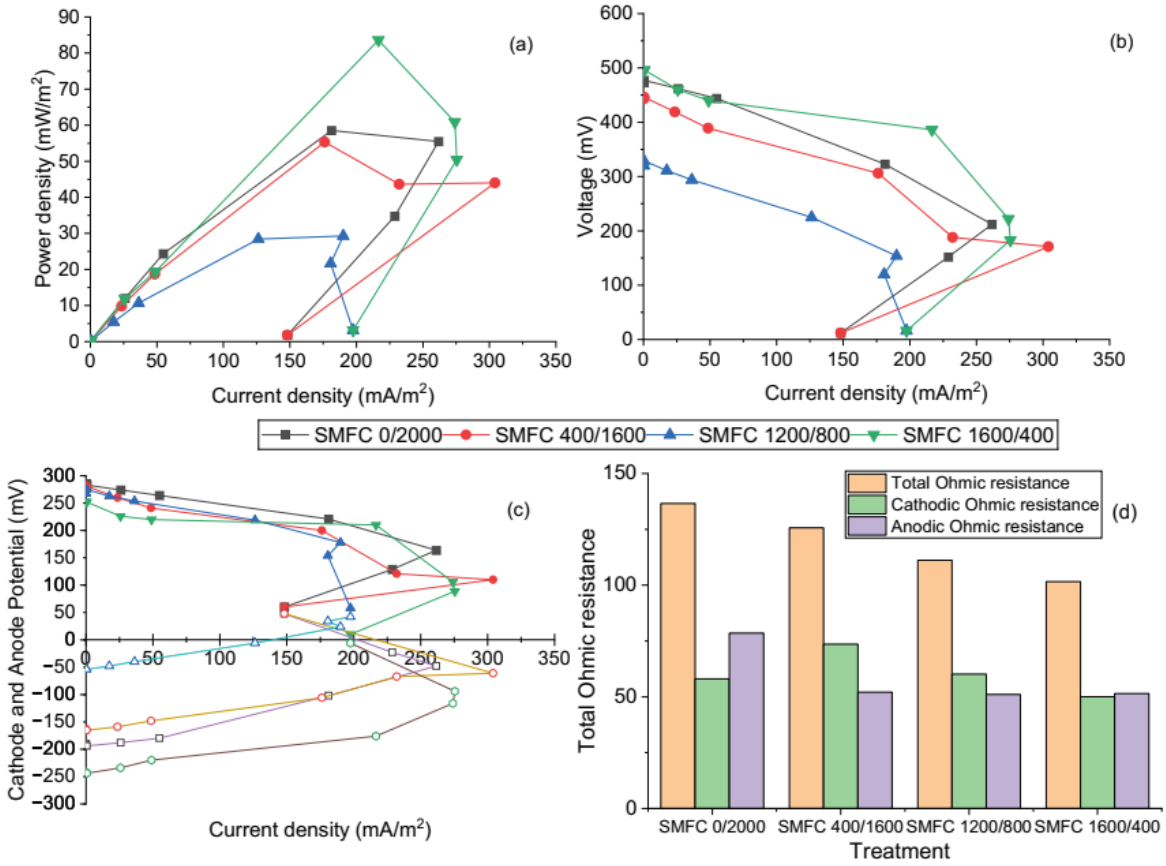

Fig. 3: Power density and polarization of SMFC with and without *S. platensis*. (a) power density graph; (b) polarization graph (c) anode-cathode polarization graph (d) Ohmic resistance graph

thereby enhancing the oxygen reduction reaction (ORR) in MFCs. Ling *et al.* (2019) showed that submerging 75% of the electrode in microalgae catholyte increased DO levels in MFCs.

Polarization Graph

Polarization analysis was conducted on day 28 using various external resistances ranging from 560,000 Ω to 10 Ω. The 1600/400 SMFC system achieved the highest power density (83.61 mW/m²) at 216.61 mA/m² and 386 mV. In contrast, the 0/2000, 400/1600, and 1200/800 ratios yielded 58.54, 55.32, and 29.27 mW/m², respectively (Fig. 3a). The significant power density stemmed from the active photosynthetic processes of microalgae at the cathode, along with efficient electron transfer that balances the redox potential throughout the light cycle (Rajamanickam and Selvasembian, 2024; Rusanowska *et al.*, 2025). Meanwhile, Dark metabolism plays a key role in photosynthesis by supplying energy and substrates, and by regenerating nicotinamide adenine dinucleotide (NAD^+) through the oxidation of its reduced form (NADH) (Yang *et al.* 2021). This study achieved nearly twice the power density compared to MFCs using *S. platensis* under continuous 24-hour illumination by da Costa and Hadiyanto (2018). It has been shown that intermittent light exposure can alleviate the harmful impacts of light-induced stress on the organism (Maali *et al.*, 2021).

The 1600/400 system showed the highest OCV (497 mV) on day 28, while the 0/2000, 400/1600, and 1200/800 systems reached 476, 445, and 320 mV, respectively. OCV differences were linked to anodic and cathodic potential variations (Fig. 3b). The 1200/800 system demonstrated the lowest OCV, which was associated with an elevated anode potential (Fig. 3c). Within this system,

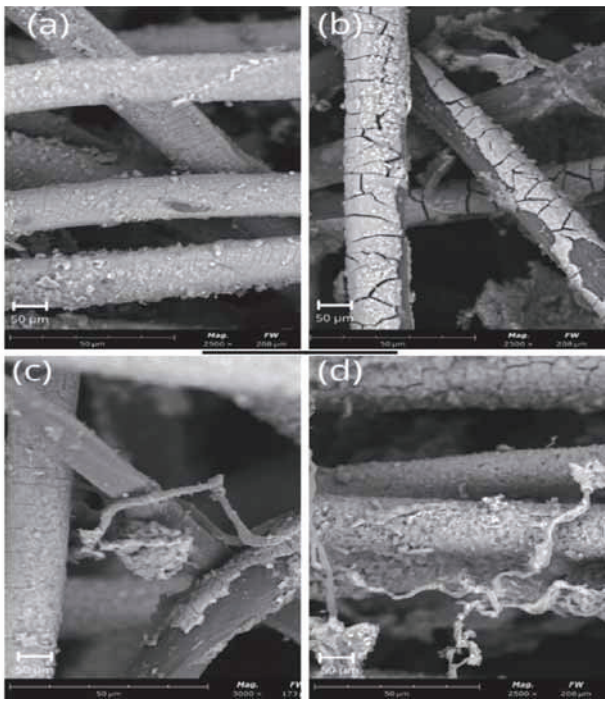

Fig. 4: SEM electrode after 28 days operation of SMFCs (a) 0/2000; (b) 400/1600; (c) 1200/800; (d) 1600/400

the anode potential became progressively more positive, whereas the cathode potential displayed a low positive value. Other systems showed a more gradual anode potential increase, reducing the risk of voltage reversal compared to the 1200/800 system. In the SMFC without microalgae (0/2000), the voltage dropped sharply from 444mV to 212 mV as the current density increased from 54.81 to 261.73 mA/m². Simultaneously, the anode potential increased from -180 mV to -48 mV (Fig. 3c). The more positive value of anode potential, indicated that the oxygen diffused on the anolyte. Oxygen produced during the day through photosynthesis was directly correlated with the generation of voltage. In contrast, during the night, the microalgae utilized oxygen for respiration, leading to a decrease in voltage. Oxygen plays a crucial role as the electron acceptor in the cathode during daytime operation (Ucar *et al.*, 2017). The microalgae–bacteria synergy reduced internal resistance and improved system performance (Aiyer, 2021). The open-circuit voltage (OCV) values noted in the polarization curve illustrate the thermodynamic behavior. The relationship between moderate current density and voltage is typically represented by the linear portion of the polarization curve. A slope in this region indicates ohmic resistance (Fuller and Harb, 2018). The polarization data (Fig. 3d) illustrate the ohmic resistance for each experimental setup. As predicted, the SMFC featuring a 0/2000 ratio demonstrated the greatest level of ohmic resistance (136.61 ohm). At moderate current densities, the voltage in this setup dropped rapidly, highlighting significant ohmic resistance. The 1600/400 has the lowest ohmic resistance than other cases (101.56 ohm). This behavior emphasizes the vital importance of microalgae in alleviating internal resistance and boosting the electrochemical performance of the SMFC system.

SEM analysis

After 28 days, scanning electron microscopy (SEM) analysis of the cathode electrode revealed the presence of *S. platensis* attached itself to the surface, creating biofilms. Numerous studies have employed SEM analysis to verify biofilm development on electrodes (Yuvraj and Aranganathan, 2017). Biofilm thickness varied by setup, with the 1600/400 system showing the thickest layer and filamentous structures, likely *S. platensis*, on the cathode. These were seen only in microalgae-containing systems (Fig.

4d). Systems incorporating microalgae demonstrated significantly thicker biofilms compared to the SMFC without microalgae (0/2000) (Fig. 4a). However, the biofilm layers in the 400/1600 (Fig. 4b) and 1200/800 (Fig. 4c) setups were less robust than those in the 1600/400 (Fig. 4d) and 0/2000 configurations (Fig. 4a). The biofilm percentage coverage area was analyzed using the open source software ImageJ (Mountcastle *et al.*, 2021). The 1600/400 had the highest percentage on quantification of biofilm (99.82%). Meanwhile, the SMFC without *S. platensis* had the lowest biofilm coverage (83.97%). It was indicated that additional *S. platensis* support the biofilm growth on electrode. However, The 1200/800 only has 87.92% of biofilm coverage. The presence of unattached or damaged biofilm on the electrode surface indicates that voltage reversal has likely occurred within the system. Prolonged voltage reversal has been identified as a key factor causing biofilm degradation, as reported by Li *et al.* (2017). Furthermore, the deterioration of the biofilm on the electrode can lead to heightened turbidity in the water phase, mainly caused by electrode corrosion and the release of biofilm particles (Li *et al.*, 2017). This underscores the importance of maintaining system stability to preserve bio-film integrity and enhance the performance of SMFC systems.

The phenomenon of voltage reversal is largely attributed to the imbalanced kinetics of the bioanode, which is shown by the variation in anodic potentials, whereas the cathodic potentials remain unchanged. It occurs when current demand exceeds the bioanode's capacity, causing the anode potential to turn positive. After reversal, oxygen production dominates at the anode (Li *et al.*, 2017).

Organic and Nutrient Removal

The combination of SMFCs and *S. platensis* markedly increased the removal of chemical oxygen demand (COD) in both the cathodic and anodic sections (Fig. 5a). The 1200/800 SMFC system exhibited a marked and statistically significant reduction in COD concentrations over the 28-day operational period. In pore water, COD levels declined from 555.00 ± 27.75 mg/L to 223.44 ± 11.17 mg/L ($p = 0.0018$), while in the overlying water, concentrations decreased from 139.44 ± 6.97 mg/L to 69.42 ± 8.37 mg/L ($p = 0.0025$). These findings underscore the system's effective performance in organic matter removal. It outperformed the 1600/400, 400/1600, and 0/2000 systems (Fig. 5a and 5b). This trend aligned with the Loss on Ignition (LoI) values observed in the sediment, where the 1200/800 sample exhibited the highest reduction in LoI, measured at from 6.44 ± 0.71 % to 3.20 ± 0.42% after 28 days ($p = 0.0019$) (Fig. 5c). In addition, *S. platensis* exhibited a catalytic role in boosting cathode performance. These findings align with Hadiyanto *et al.* (2020), who reported a 67 ± 5% COD reduction in tapioca waste using an MFC system. Meanwhile the 1200/800 SMFC system reached 50.26 ± 1.46% for COD removal at overlying water and 79.34± 4.25% for COD removal at pore water. Nonetheless, it is essential to optimize the concentration of *S. platensis* in SMFC systems to achieve a balance between electricity generation and the efficiency of pollutant removal (Hadiyanto

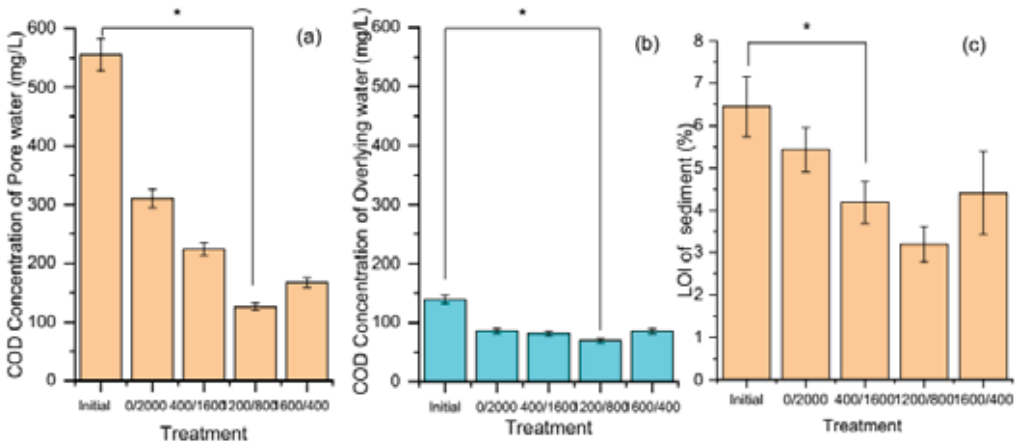

Fig. 5: (a) COD concentration at pore water and overlying water, and (b) LoI at sediment

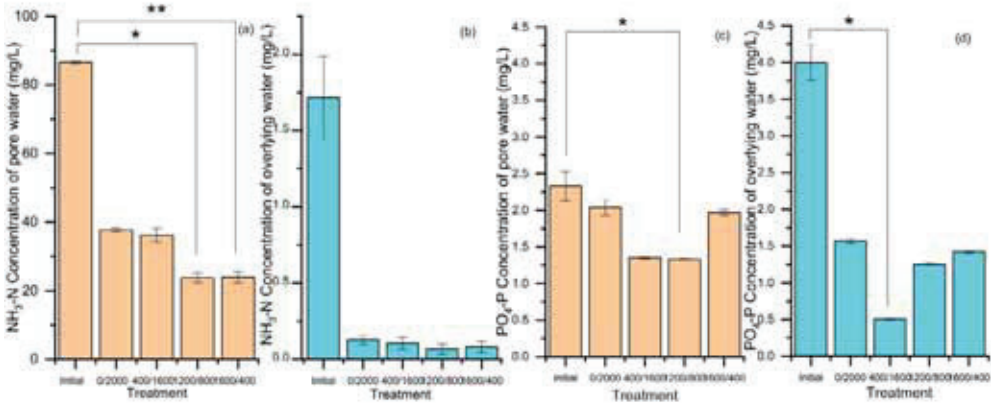

Fig. 6: (a) NH_3-N concentration in pore water, (b) NH_3-N concentration in overlying water, and (c) PO_4-P concentration in pore water and overlying water

et al., 2023). The reduction in COD concentration in overlying and pore water, as well as LoI in sediment, is illustrated in Fig. 5(a), 5(b), and 5(c). The 1200/800 system achieving the lowest concentrations across all compartments after 28 days. This implies that the inclusion of *S. platensis* enhances the degradation of organic compounds within both anode and cathode chambers. The relationship between current density production and COD removal is evident in Fig. 2. The 1200/800 system showed the highest early-phase current density, aligning with strong COD removal. With the decrees in COD, there was a rise in activation losses, which over time diminished the current density. Oxygen was produced through photosynthesis during the light cycle. This oxygen could have diffused into the anode, possibly suppressing the activity of anaerobic bacteria (Lu and Imlay, 2021). The ORP value became more positive, showing the presence of oxygen. In the 1200/800 treatment, sediment ORP rose from –153 ± 3.51 mV to –118 ± 11.78 mV. This suggests oxygen was present. As a result, current density in this treatment was lower.

The polarization curve (Fig. 3b) illustrated that the 1200/800 system underwent a pronounced early voltage decline. This reflects considerable variations in internal resistance attributed to COD and LoI decomposition. COD levels also correlated with chlorophyll-a, suggesting pollutant adsorption–desorption dynamics (Song *et al.*, 2020). These findings underscore the critical role of microalgae.

Fig. 6a, b, c, and d illustrates the dynamics of NH_3-N and PO_4-P concentrations in the overlying water and pore water. After 28 days, the SMFC with a 1200/800 ratio demonstrated the lowest concentrations of NH_3-N and PO_4-P, followed by 1600/400, 400/1600, and 0/2000 ratios. Specifically, the SMFC with 1200/800 showed significant difference between initial value of NH_3-N in pore water 86.62 ± 0.48 mg/l and NH_3-N concentration of 1200/800 with value 23.75 ± 1.44 mg/L (p=0.0035). The initial concentration of NH_3-N in pore water also showed significant difference with 1600/400 concentration on 23.93 ± 1.62 mg/L with p=0.0047. Meanwhile, the NH_3-N from 1.72 ± 0.27 mg/L to 0.06 ± 0.03 mg/L in overlying water. Based on the results, the addition of microalgae significantly promoted the release of NH_3-N from sediment therefore NH_3-N in porewater reduced. SMFCs with added microalgae removed NH_3-N more effectively than those without, consistent with previously published studies (Song *et al.*, 2020). As shown in Fig. 6c, PO_4-P concentrations in initial (2.33 ± 0.20 mg/L) showed significant different with PO_4-P concentrations in 1200/800 in pore water (1.33 ± 0.01 mg/L) with p=0.0013. The initial value of PO_4-P concentrations in overlying water 4.00 ± 0.24 mg/L reduced the PO_4-P concentrations in 1200/800 1.25 ± 0.02 on mg/L with p value = 0.0010. The use of electrodes boosted nitrogen fixation in sediments and lowered the amount of exchangeable nitrogen. Furthermore, microalgae played a role in converting organic phosphorus into inorganic phosphorus (Song *et al.*, 2020). However, the reduction of phosphate in sediment was less than in the overlying water. The biomass of phytoplankton such as microalgae was cruicial on the accumulation of bioavailable phosphorus in sediment (Ni *et al.*,

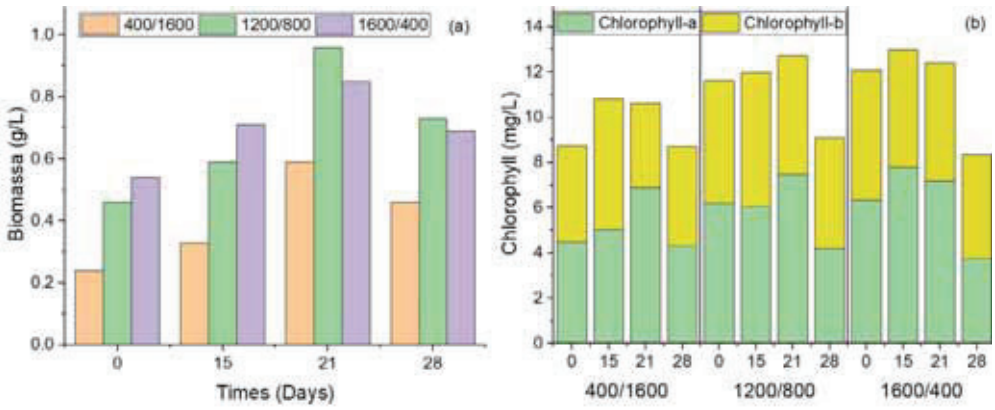

Fig. 7: (a) Biomass and (b) Chlorophyll of *S. Platensis* in cathodic chamber of SMFCs

2019). The pH of the sediment and overlying water decreased across all cases compared to the initial pH. After 28 days of operation, the sediment pH of 1200/800 decreased from 9.81 ± 0.39 to a range of 7.10 ± 0.07. This reduction in pH can be linked to the emission of organic acids that occur during the decomposition of organic matter (Patil *et al.*, 2022). A pH of 7–8 is optimal for *S. platensis* and electrogenic bacteria, boosting organic degradation and energy generation (Hadiyanto *et al.*, 2022). The metabolic rate of *S. platensis* and electrogenic bacteria is greatly influenced by temperature. During this experiment, the temperature was kept stable at 26–27°C. The ORP value of the overlying water became more positive than the initial ORP value (296.33 ± 3.51 mV), particularly in the SMFC with *S. platensis*. For example, the SMFC with a ratio of 0/2000 exhibited an ORP value of 391.00 ± 8.54 mV. Meanwhile, SMFCs with ratios of 400/1600, 1200/800, and 1600/400 showed ORP values of 435.33 ± 9.60 mV, 459.33 ± 2.52 mV, and 453.67 ± 2.08 mV, respectively. ncreased ORP values point to a higher oxygen level in the water above, likely attributed to the photosynthetic activity taking place in the cathodic chamber (Hadiyanto *et al.*, 2023).

S. platensis biomass and chlorophyll analysis

The growth of *S. platensis* within the microalgae-SMFC system is a critical consideration, as its photosynthetic activity plays a vital role in oxygen production. From day 0 to day 21, the biomass of *S. platensis* demonstrated an upward trend across all experimental conditions (Fig. 7a). During early 15 d, the SMFC with 1600/400 led the growth of biomass. Then, the 1200/800 condition achieved the highest biomass levels during day 21 (0.96 g/L). Nonetheless, following day 21, there was a decrease in biomass production across all scenarios. This reduction is linked to a drop in both biomass and chlorophyll levels, as depicted in Fig. 7a and b. The decrease likely results from nutrient depletion and organic degradation by *S. platensis* and SMFC activity. The maximum concentration of biomass and chlorophyll contributed to increased photosynthetic activity. Consequently, this caused an oversaturation of oxygen at the cathode, with oxygen diffusing into the anode area (Lu and Imlay, 2021). As reported by Zheng *et al.* (2016), uncontrolled algal growth in MFCs can alter catholyte composition, affecting pH, conductivity, which compromises system performance. As a result, the 1200/800 treatment showed the lowest current density compared to 400/1600 and 1600/400. Several researchers have found that microalgae biomass is closely linked to MFC/SMFC performance (Table 2). *S. platensis* thrives at the cathode, aiding in electricity production. The pigments chlorophyll-a and chlorophyll-b play a vital role in starting the photosynthesis of microalgae (Fadhil and Ismail, 2023). The initial chlorophyll concentration increased and reached the peak at 21 d for 400/1600 and 1200/800. The SMFC with ratio 1600/400 has highest total chlorophyll at 15 d (8.48 mg/L) than slightly decrease at 21 d (7.68 mg/L). Initial chlorophyll-a levels varied with the *S. platensis* to water ratio: 2.49, 4.33, and 4.51 µg/mg for 400/1600, 1200/800, and 1600/400, respectively. The 1600/400 SMFC later

Table 2: Recent publication with combining microalgae and MFC or SMFC

Strains	Anode substrat	Cathodic	Electricity production	Polutan removal and growth of microalgae	Sources
Chlorella vulgaris in SMFC system	River sediment	River water and *C. Vulgaris* was grown in BG-11 media	Power density : 3.46 mW/m² Current density : 32.39 mA/m²	COD removal : 65.27% Biomass: 0.031 kg/ m^3/day	Sharma *et al.*, 2021
Chlorella vulgaris in SMFC system	Local dye textile wastewater treatment plant	Local dye textile wastewater treatment plant	Power density : 2,25 – 6,46 mW/m²	COD removal : 92%	Logroño *et al.*, 2017
Chlorella vulgaris in SMFC system	Lake sediment	Lake water and *C. Vulgaris* was grown in BG-11 media	Power density : 28.4 mW/m²	Organic removal : 37.31%	Song *et al.*, 2020
Spirulina platensis in MFC system	Tapioca wastewater	tapioca wastewater and *Spirulina platensis* is diluted	Power density: 44.33 mW/m²	-	da Costa and Hadiyanto, 2018
Dunaliella salina	Synthetic wastewater	Natrium Chloride with Modified Johnson's Medium	Power density: 213.38 mW/m^2	Maxium COD removal 59.32%	Mishra and Chhabra, 2022
Scenedesmus obliquus	Petroleum wastewater	Blue Green-11 medium	maximum Power density=3.37 mW/m^2	Maximum COD removal 68%	Ashwaniy and Perumalsamy, 2017
Spirulina plantesis in SMFC system	Artificial lake sediment	*S. platensis* with artificial lake water	1600/400 produced highest Current density: 48.43 mA/m² Power density graph: highest power density on 1600/400: 83.61 mW/m^2.	1200/800 highest removal 50.26 ± 1.46% for COD removal at overlying water and 79.34± 4.25% for COD removal at pore water in Biomass production: 0.96 g/L; Chlorophyll-total : 11.4 mg/L	This study

reached the highest level at 8.48 µg/mg, followed by 1200/800 and 400/1600 (Fig. 7b). Light intensity plays a crucial role in chlorophyll production, microalgae development, and photosynthetic activity. As light intensity rises, chlorophyll-a levels increase, while chlorophyll-b tends to decrease. This study described that increasing amount of total chlorophyll relevant to high ratio *S. platensis* in the cathode of SMFCs. It was indicated that synergism *S. platensis* and SMFC. The Chlorophyll (a,b) content supports the photosynthesis process to produce oxygen as an electron acceptor in SMFC (Ucar *et al.*, 2017). Consequently, the electricity rose as the total chlorophyll levels increased. Nevertheless, the presence of oxygen in the interface between the overlying water and sediment leads to reduced current production (Saba *et al.*, 2017).

Based on the data in Table 2, it can be seen that the electricity production and pollutant removal results in this study are not significantly different from previous studies. In this study, with a ratio of 1600/400, the power density was 83.61 mW/m^2, almost double the value compared to the study by da Costa and Hadiyanto (2018). In this study, *S. platensis* achieved a power density nearly twice that of Chlorella vulgaris in SMFCs with lake water and sediment, which only produced 28.4 mW/m² (Song *et al*, 2020). However, Dunaliella salina showed a much higher power density of 213.38 mW/m², likely

due to the use of sodium chloride and Modified Johnson's Medium as the catholyte (Mishra and Chhabra, 2022). In contrast, Scenedesmus obliquus using BG-11 as catholyte and petroleum wastewater as anolyte generated only 3.37 mW/m² (Ashwaniy and Perumalsamy, 2017). Moreover, the removal efficiency of ammonia pollutants from pore water reached 72.60%, which is near the 66.61% removal efficiency found in the research conducted by Sharma *et al*. (2021). Meanwhile, the removal value of phosphate in the overlying water in this study, with a value of 72.60%, was lower than the study by Sharma *et al.* (2021) of 95.59%.

CONCLUSION

This study provides comprehensive insights into the integration of *Spirulina platensis* in Sediment Microbial Fuel Cell (SMFC) systems. It specifically emphasizes its function in electricity generation, the breakdown of organic matter, nutrient cycling, and the production of microalgal biomass. The experimental design varied the volumetric ratios of *S. platensis* and overlying lake water. The findings of this study underscored the essential role that microalgal concentration plays in system performance. The SMFC configuration with a 1600/400 (*S. platensis*/water) ratio achieved the highest current density (48.43 mA/m²). It was facilitated by robust photosynthetic activity and efficient electron transfer between electrodes. The use of scanning electron microscopy (SEM) validated the substantial formation of biofilm presence on the cathode, characterized by filamentous structures from *S. platensis* colonies that boost cathodic reactions. Conversely, the 1200/800 treatment yielded the highest performance on pollutant removal and microalgal biomass production. The 1200/800 mL showed in the overlying water, COD decreased from 139.44 ± 6.97 mg/L to 69.42 ± 8.37 mg/L ($p = 0.0025$), while NH_3-N was reduced from 1.72 ± 0.27 mg/L to 0.06 ± 0.03 mg/L. The initial value of PO_4-P concentrations in overlying water 4.00 ± 0.24 mg/L reduced the PO_4-P concentrations in 1200/800 1.25 ± 0.02 on mg/L with p value = 0.0010. It was alongside superior biomass (0.96 g/L) and chlorophyll production. These results indicate a trade-off between optimizing energy output and maximizing pollutant remediation. The reduction in biomass and chlorophyll concentrations following day 21, probably resulting from nutrient exhaustion and the decomposition of organic matter, highlights the critical need for ongoing resource availability to ensure optimal system performance. The findings reinforce the dual functionality of *S. platensis* in SMFCs—not only as an oxygen producer and catalyst for enhanced electricity generation but also as an agent for improving water quality through bioremediation. Therefore, integrating photosynthetic microalgae such as *Spirulina platensis* presents a promising strategy for advancing sustainable bio-electrochemical systems. Future studies should focus on enhancing microalgal concentrations, extending operational duration, and establishing a continuous nutrient supply to boost long-term system stability and energy conversion efficiency. Furthermore, more studies are necessary to examine the long-term operational performance of SMFCs in outdoor or real environmental settings, analyze the scalability of the system, carry out detailed techno-economic assessments, and guarantee safety to promote practical applications.

AUTHOR CONTRIBUTIONS

N.I. Oktavitri, the corresponding author, has contributed in supervising the experiment, financial support, manuscript preparation. A. Soegianto ase second author has contributed in the data analysis of microalgae growth, D.R.M. Isnadina has contributed in the data analysis of environmental analysis, M.H.F. Amin has supported in manuscript preparation, A. Chakraborty and W-E. Thung has contributed in data validation and data verification, D.K. Rahmadhani dan M.A. Saputra has contributed in data collection, K. Kim has supported in the conceptual experiment and writing review.

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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.

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ABBREVIATIONS

%	Percent
°C	Degree Celsius
Ω	Ohm
A	Area of electrode
Ag/AgCl	Silver per silver chloride electrode
APHA	American Public Health Association
CCV	Close circuit voltage
Chlorophyll a	Chlorophyll type a
Chlorophyll b	Chlorophyll type b
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DO	Dissolved oxygen
e^-	electron
GF/C	Glass fiber grade C
H^+	Ion hydrogen
i	Current density
I	Current
LDPE	Low-density polyethylene
LoI	Loss on ignition
m^2	Meter square
mA/m^2	mili Ampere per meter square
MFCs	Microbial Fuel Cellss
mL	mili liter
mV	mili Volt
mW/m^2	mili Watt per meter square
NH_3-*N*	Ammonia nitrogen
O_2	Oxygen
OCV	Open circuit voltage
ORP	oxidation-reduction potential
ORR	Oxygen reduction reaction
P	Power density
pH	Potential of hydrogen
PO_4-*P*	Phosphate phosphorus
R	Resistance
SEM	Scanning electron microscopy
S. Platensis	*Spirulina platensis*
TLD	Tubular light type D
UV-VIS	Ultraviolet-Visible Spectroscopy
V	Voltage
V/V	Volume per volume
SEM	Scanning electron microscopy
SMFCs	Sediment microbial fuel cells

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ORIGINAL RESEARCH PAPER

Water-energy-carbon cost of compensating atmospheric water losses from open irrigation ponds in arid regions

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ABSTRACT

BACKGROUND AND OBJECTIVES: Open irrigation ponds are commonly used for agricultural water storage but lose significant water amounts to evaporation. The energy and environmental implications from these losses in water-scarce areas, where conservation takes precedence, are not thoroughly studied. The objectives of this study were to examine water, energy, and environmental impacts of evaporation losses in the Jordanian Badia to identify insights for sustainable agricultural practices.

METHODS: Field surveys were conducted at 20 farm sites in the northern Jordanian Badia to assess pond usage and water management practices. The study utilized novel methods including open-access meteorological data and sensor-based validation to record dynamic changes during the irrigation season. The study further analyzed the environmental effects by utilizing the carbon equivalent factor in conjunction with information regarding water and energy consumption, which has not been tackled before in the region.

FINDINGS: In the study area, drip irrigation emerged as the predominant choice because of water scarcity, while soilless systems and sprinkler irrigation were far behind. On-farm storage systems were widely used (70 percent) in the region due to water supply issues, but only 20 percent of farmers used closed tank systems. In the summer months, evaporation exceeded 220 millimeters monthly, leading to annual water losses of over 4500 cubic meters per pond. These losses required an estimated 1635 kilowatt hours of energy per 1000 cubic meters of water pumped. Annual energy consumption per pond reached approximately 2000 kilowatt hours, resulting in up to 1200 kilograms of carbon dioxide equivalent per year. This accounted for almost 1 million cubic meters in water losses, 100,000 dollars in costs, and over 200 tons of equivalent carbon emissions to replace evaporation losses every year.

CONCLUSION: Evaporation losses from irrigation ponds significantly reduce water use efficiency and increase energy and environmental costs. This was despite the various water conservation techniques in the region. These losses can be slightly reduced through low-cost measures such as reducing pond water levels. Additionally, utilizing more effective solutions like floating solar panels can greatly decrease costs, but this comes with a considerable financial commitment. Implementing such practices supports sustainable agriculture and aligns with national water conservation priorities, but requires sound policy interventions.

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INTRODUCTION

Fresh water is one of the most valuable limited resources worldwide. This resource has been significantly utilized owing to the increase in population growth and the advancement of industrial and agricultural sectors (Mekonnen *et al.,* 2016). Reducing the pressure on freshwater resources has been the focal point of many researchers worldwide (Pérez-Sánchez *et al.,* 2024; Bani-Melhem *et al.,* 2023a and b). Among the different sectors contributing to this pressure, agriculture stands out as the largest consumer of freshwater globally, with farmers being one of the groups most directly affected (Al-Kilani, 2024). Moreover, with increasing drought impacts on agriculture and climate projections of rainfall variability, the reliance on irrigation may increase by over 20 percent (%) (Al-Kilani *et al.,* 2024b; Rosa *et al.,* 2020; Purwantoro *et al.,* 2024). A significant number of researchers have turned their attention to the conservation of freshwater via effective irrigation management (Al-Kilani *et al.,* 2024a; França et al., 2024). Other researchers focused on wastewater treatment and reuse (Al-Kilani and Bani-Melhem, 2025; Bani-Melhem and Al-Kilani, 2023; Murrell *et al.,* 2021). Improved monitoring of agricultural water resources and smart systems also receives increasing attention (Abdelal *et al.,* 2025; 2019). Moreover, there has been a growing emphasis among researchers on the water losses occurring in natural and artificial reservoirs as part of irrigation management strategies for conserving water. Many farms depend on open water bodies or artificial ponds for irrigation. There are over 277,000,000 irrigation ponds with area less than one hectare (ha) and over 24,000,000 with area between 1 to 10 ha globally (López-Felices *et al.,* 2020). Although these ponds are essential for irrigation, they lose significant amount of water through evaporation due to their large surface area that is exposed to the atmosphere (Saggaï and Bachi, 2018). Several studies investigated water losses through evaporation from open surfaces. Between 12.1 and 15.4 billion cubic meters (m^3) of water losses to evaporation have been reported from lake Nasser in Egypt (El-Shirbeny and Abutaleb, 2018). Furthermore, reports indicate that around 40-60% of the volume of the water reservoir in Lake Tahoe has been lost as a result of evaporation (Friedrich *et al.,* 2018). This drew researchers' attention to look for innovative solutions to reduce these losses. So far, researchers examined covers as solutions to reduce water surface area exposed to atmosphere (Elsebaie *et al.,* 2017). These can be categorized to physical, chemical, and biological covers. The physical covers are designed as floating or shading structures that partially reflect solar radiation and obstruct water-air interaction, which helps to stop water vapor from reaching the atmosphere. Such covers could offer up to 95% reduction of evaporation (Youssef and Khodzinskaya, 2019). Chemical covers are synthetic substances that inhibit water-air interaction by forming thin layer at the surface of water (Saggaï and Bachi, 2018). However, these could be broken down by wind. Biological covers are made up of organic materials or plants that effectively block water-air interaction, like floating palm fronds, potentially achieving a reduction in evaporation of up to 75% (Elsebaie *et al.,* 2017). Although these solutions show significant efficiency, they still have some limitations. The high cost prevents the adoption of the of the physical covers, and some studies emphasis the large water footprint for manufacturing these covers (Han *et al.,* 2019). Also, chemical and biological covers are limited through their short life span and low efficiency (Han *et al.,* 2019). Concerns about water ecology were expressed when implementing these techniques, but this does not pose a major problem for agricultural practices in irrigation ponds (Shalaby *et al.,* 2021). Understanding the implications of evaporation losses from irrigation ponds can offer valuable insights for improving agricultural water use. This is particularly true in arid and water-stressed environments, where conservation is essential. Farmers in the Jordanian Badia, one of the world's most water scarce regions, apply a wide range of water conservation techniques. This includes water harvesting, deficit irrigation, and treated wastewater reuse, amongst other strategies (Al-Kilani, 2024; Shammout *et al.,* 2018). Furthermore, the Badia's institutional policies feature subsidized water charges along with zero-interest agricultural loans. This makes the Badia an interesting site to explore the factors and implications of agricultural water management and storage systems. This allows understanding whether the accumulated experience in drought mitigation in the region has reflected on managing the issues related to evaporation losses. Specifically, examining the implications of evaporation losses on water, energy, and the environment is vital, especially since past research

has mainly focused on the quantities of water lost. To explore this gap, a field survey was conducted at 20 farm sites in the north Jordanian Badia, focusing on how irrigation ponds are used and how water is managed. The objective of this study is to identify the resulting impacts of compensating water losses from evaporation in terms of water, energy, and carbon footprint. This would facilitate a more thorough understanding of the sustainability trade-offs related to surface water storage in the agricultural sector of Jordan. This study aimed to identify opportunities for more efficient practices under increasing climate and resource pressures. This study was conducted in Jordan within the governorates of Mafraq, Zarqa, and Azraq between 2021 and 2023.

MATERIALS AND METHODS

Study region and data collection

Data on irrigation systems was collected through field visits in the north Jordanian Badia. These visits were part of a technical evaluation aiming to identify on-farm management and structural aspects for improving the incomes and efficiencies of farms. A total of 20 farm units were included; these were allocated across various administrative regions within the designated governorates. Farm sites selected for visitations were generally over 10 ha in area and were actively producing crops. Smaller farms were generally avoided and farms not producing or were going through a fallow period were not included. The surveys addressed a number of aspects including agricultural water management and crop production systems. Each farm had been visited at least twice for initial examination and a more detailed survey and consulting. The target region is generally characterized by arid and semi-arid conditions, and generally receives 50 – 300 millimeters (mm) of annual precipitation (Al-Kilani *et al.,* 2021). The conditions can be described as unreliable for rain fed crop production and irrigation is essential. The methodology of the study consisted of determining the area of irrigation ponds using a measuring tape, which was then succeeded by evaluating water losses from evaporation. Farmers have been compensating for this loss by extracting water from the source, typically groundwater, leading to an estimated energy waste based on the evaporation volume. A novel method was adopted in this study due to the limited data that farmers provide on water and energy consumption, which was the use of open-access datasets and sensor-based validation. Evaporation data was obtained from an open-access reference evapotranspiration (ET) datasets in the water productivity portal (WaPOR) for the study region. This dataset uses a modified version of the ET-Look model based on the Penman-Monteith equation. The methodology combines remote sensing data with meteorological inputs such as solar radiation, air temperature, wind speed, and humidity. The output of this method is the amount of water that would evaporate, sometimes referred to as "potential evaporation". The model processes satellite-derived parameters like surface albedo and land cover, along with interpolated weather data, to produce spatially distributed values. Initially, the energy balance is calculated, followed by the derivation of reference evapotranspiration utilizing standardized values for surface and aerodynamic resistance. This approach allows consistent and regular estimation of ET over large regions, even in areas with limited ground weather data. Encouragement for utilizing these types of data sources has been observed with reduced limitations in regions like Jordan (Al-Kilani *et al.,* 2025; Al-Omoush *et al.,* 2025). The evaporation datasets were validated using an irrigation pond with an ultrasonic sensor installed on it to measure the change in water level in the pond. The ultrasonic measurements dataset comprised 117 measurements, validated by manual depth measurements of the pond depth. Due to the significant effort involved in visiting the site, only a few manual readings were captured, which were inadequate for producing any error metrics. However, the few manual readings recorded were identical to the sensor measurement. Previous works have shown that Arduino-based ultrasonic sensors for measuring water level are reliable even under turbulent conditions (Pereira *et al.,* 2022).

Calculations and data analysis

The volume of water loss (m^3) was determined based on the average surface area of an irrigation pond in square meters (m^2) in the study region and estimated evaporation in meters (m), using Eq. 1 (Abdelal, 2021):

$$Water\ loss\ volume = Pond\ Surface\ Area \times Evaporation\ depth \quad (1)$$

Energy consumption in kilowatt-hours (kWh) resulting

from supplementing water losses to evaporation was calculated based on the specific energy consumption (SEC), using Eq. 2 (Abdelal *et al.,* 2024):

$$Energy\ consumption = SEC \times Water\ loss\ volume \quad (2)$$

SEC was physically determined based on the energy requirement formula, which uses the density of water (ρ), gravitational acceleration (g), total dynamic head (TDH) and pump efficiency (η), using Eq. 3 (Abdelal *et al.,* 2024):

$$SEC = \frac{\rho \times g \times TDH}{\eta \times 3.6 \times 10^6} \quad (3)$$

TDH and η were estimated based on an assessment of the water system components and design from field visits, while the term (3.6×10^6) converts SEC from joules to kWh. The carbon footprint that results from mitigating atmospheric water losses was quantified as the carbon dioxide equivalent emissions (CO2e) associated with the pumping process. This was calculated using the national emission factors for the national energy grid in Jordan. Testing the agreement between measured (x) and estimated (y) evaporation time series was done using Pearson's correlation (R), using Eq. 4 (Al-Kilani *et al.,* 2025):

$$R = \frac{\Sigma(x_i - \bar{x}) \times (y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \times \Sigma(y_i - \bar{y})^2}} \quad (4)$$

The accuracy of the estimations in terms of error was evaluated using the mean absolute error (MAE), using Eq. 5 (Abdelal and Al-Kilani, 2024). Where, x and y represent data points from the measured and estimated datasets at time (i), respectively.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|x_i - y_i| \quad (5)$$

RESULTS AND DISCUSSION

Agricultural water management

The farms had a wide range of cultivation practices including mixed cropping, crop rotations, greenhouses, and soilless systems. Drip irrigation was the most widely used agricultural water management system, and several farmers utilized multiple irrigation methods on their farms (Fig. 1). Most farms had a plot where drip irrigation was applied, even when other systems were available. Drip irrigation is popular approach because of the severe water scarcity in the region and the high irrigation efficiency commonly associated with drip irrigation (Amdar *et al.,* 2025). The second most preferred alternative was soilless culture, especially ditch hydroponics systems, known for their remarkable efficiency in water consumption (Abdelal *et al.,* 2024). The least common type in the study region was sprinkler irrigation, which commonly has a lower irrigation efficiency compared to drip irrigation.

Determining the rate of water consumption among

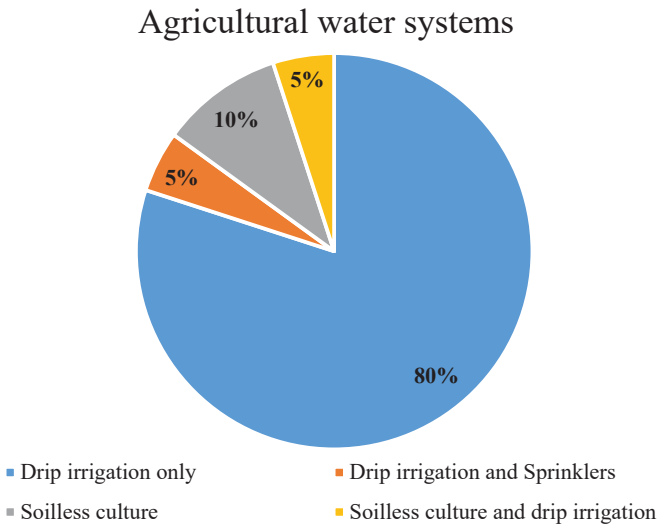

Fig. 1: Agricultural water systems adopted by the surveyed farmers in the North Jordanian Badia

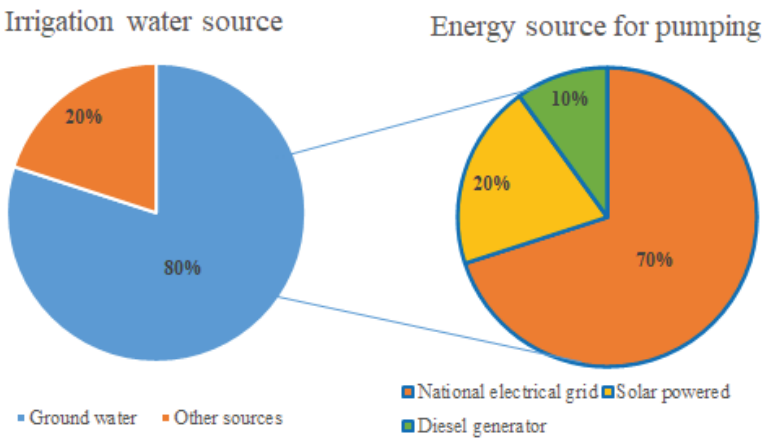

Fig. 2: Irrigation water sources and energy sources used in the study region

Table 1: Water costs on the farmer in the study region

Water source	Price range ($US/m^3)
Ground water pumping (onsite)	0.1-0.5
Sourcing ground water from surrounding owners	0.4-1.4
Sourcing treated wastewater	0.8-1.5
Hauling water by trucks	1.8-2.5

farmers accurately proved to be impossible, as they did not keep track of their monthly water usage. Instead, farmers were mainly interested in recording their seasonal water costs, which are related to varying water costs and pricing systems. Also, farmers are discrete about this information as it may cause legal issues for them due to the strict water use policies in Jordan. In this regard, researchers and non-governmental entities can significantly contribute to enhancing data transparency, owing to their more effective outreach to farmers (Al-Kilani, 2024; Elahi *et al.,* 2018). This allows more accessibility to data without compromising the farmers' legal standing. This requires ensuring that sensitive information is handled with confidentiality and used solely for research and policy development purposes. The evaluations made by farmers regarding their water costs, pricing, and consumption were not uniform. However, it can be estimated that farmers' monthly water consumption generally exceeded 2500 m^3/ha for irrigation (Amdar *et al.,* 2025). The farmlands visited had diverse layouts and water systems; the majority of farmers (80%) relied on ground water wells as the main source for irrigation (Fig. 2). Other farmers relied on pipelines from the Jordanian Water Authority, treated wastewater, and water delivery tanks. A number of farmers are still making adjustments in response to the changing costs of water and other variables by switching their water sources. This is because the water costs vary significantly between different sources as shown in Table 1.

Treated wastewater was only used at 2 sites, but may become increasingly more popular in the future. This is due to decreasing water availability and potential decrease in fertilizer costs due to its nutrient content (Tarawneh *et al.,* 2024). The main source of energy for water pumping was reported as the national electric grid. Other options for energy included using diesel generators and solar power. Farmers mentioned facing some constraints on acquiring licenses for renewable energy usage, but they are anticipated to transition away from diesel generators in the near future. This information is needed for estimating the carbon foot print of supplementing atmospheric water losses from open ponds.

Water storage systems

More than half of farmers (60%) had a groundwater well within the farm, while others had off-farm water

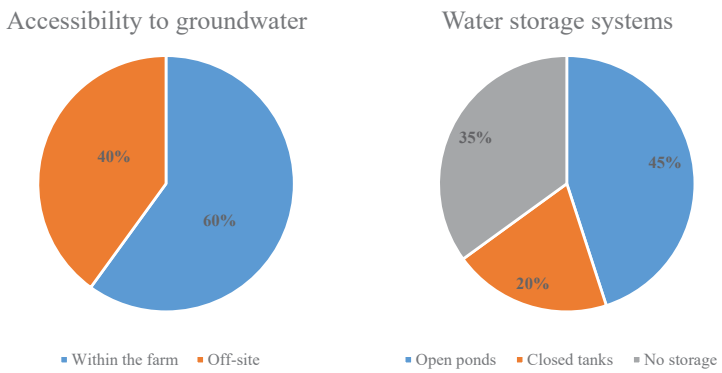

Fig. 3: Accessibility to ground water and the types water storage used in the study region

sources. Water storage methods also varied among farmers. (Fig. 3).

Some farmers did not rely on storage (35%), some used closed tanks (20%), and the most popular choice was open-air irrigation ponds. The farmers defended the implementation of storage systems as a means to avert the risk of total crop failure should there be maintenance or downtime in the water supply system. Farmers reported that the submerged water pumps used in ground water wells broke down at least once a year. Furthermore, farmers indicated that the pumping capacity from the source (such as a groundwater well) was inadequate to fulfill the irrigation needs of the entire farm, thus the storage system facilitated the distribution of water into various hydrazones. Another minor reason for using these ponds reported by few farmers was to grow fish, but this was not a popular practice. Almost all farmers that used soilless systems reported using closed tanks for storage, due to their much lower monthly water consumption (almost 1/5 compared to open-fields cultivation). Most of the open water storage ponds had a very large surface area (>1000 m^2) with over 3000 m^3 of storage capacity and were kept filled to the top (Fig. 4). Nonetheless, a number of these ponds were not dedicated to just one farmer; rather, they were collectively used by multiple farmers. The farmers collaborated on the expenses associated with the construction and upkeep of these ponds. Such costs included hiring a specialized contractor along with machinery and the plastic sheets used to coat the interior of the pond. Two layers were commonly used, a 4 micrometers layer that was changed every 2-4 years at the bottom, and a 2 micrometers layer placed over it that was changed every 1-2 years. The farms referenced employ these pond structures owing to their straightforward construction and affordability. The entire structure can be prepared in few days and its construction costs range from $500 to over $1000 depending on the size. These irrigation ponds have a large surface subjected to atmospheric water evaporative demand. Farmers recognized the possibility of water loss through evaporation and the corresponding energy costs, yet they were unclear about the degree to which this occurs. The main problems related to the coverage of ponds mentioned by farmers included:

- Water quality concerns
- The inconvenience and effort of covering and uncovering the pond
- Local costs of specialized solutions (e.g. shading balls) were too high, one supplier quoted the farmers $1-1.75 per ball.
- Lack of specialized contractors for installing pond-covering systems

The effect of closed storage on water quality could be a legitimate risk (Bani-Melhem *et al.,* 2017). However, some researchers have demonstrated that covering irrigation ponds may not compromise its water quality (Abdelal, 2021). Recently, the government required the farmers to apply for licenses to construct these ponds to limit any negative effects, especially that 3 people reportedly drowned in these ponds in the past year. Nevertheless, this policy strategy might prove ineffective because of the essential role and convenience these ponds provide to farmers. Tackling the challenges that lead farmers



Fig. 4: Images of open irrigation ponds from the study region

Table 2: Stats of information relevant to atmospheric water losses from open irrigation ponds

Parameter	Min.	Max.	Mean	Standard deviation (SD)
Area of storage ponds (m^2)	110	22800	5176.7	6955.10
Water pumping capacity (m^3/h)	10	250	167.1429	91.42
Potential evaporation during August (mm)	206.7	271.3	228.17	21.52

to use these ponds and the restrictions on covering them is a more effective approach for limiting their negative impacts.

Atmospheric water losses

In order to calculate the volume of water losses from the irrigation ponds, the surface area of these ponds was measured directly at the site. The ponds varied significantly in size as shown in Table 2; the smallest pond was around 110 m^2 while the largest pond was over 22,000 m^2. The ponds had around 5000 m^2 of surface area on average. Evaporation varied slightly between different sites; evaporation ranged between 200 mm and 271 mm during peak seasons.

To ascertain that the evaporation estimates referenced in this study accurately depicted the water losses from irrigation ponds, an experimental pond was established. The water level in the pond was monitored using an ultrasonic sensor, the only losses in the pond was to evaporation, no water was abstracted from the pond for any purpose. This experiment was carried out in advance of the field visits and persisted several months. There were many missing values due to using a very simply setup based on an Arduino microprocessor, but there were sufficient measurements for validation. Regression (R^2) was modest (0.57), likely due to validating at a daily scale instead of monthly (Fig. 5). However, the validation results based on R, MAE, and root mean squared error (RMSE) demonstrated good consistency between measured and estimated evaporation losses (Table 3). The assessments usually overestimated daily evaporation by merely 1.27 mm, implying that the quantitative outcomes of the water loss analysis can be highly trustworthy.

Fig. 6 shows the monthly evaporation and the average cumulative volume of water loss from an irrigation pond due to evaporation for the years 2021, 2022, and 2023. The blue dashed line illustrates the

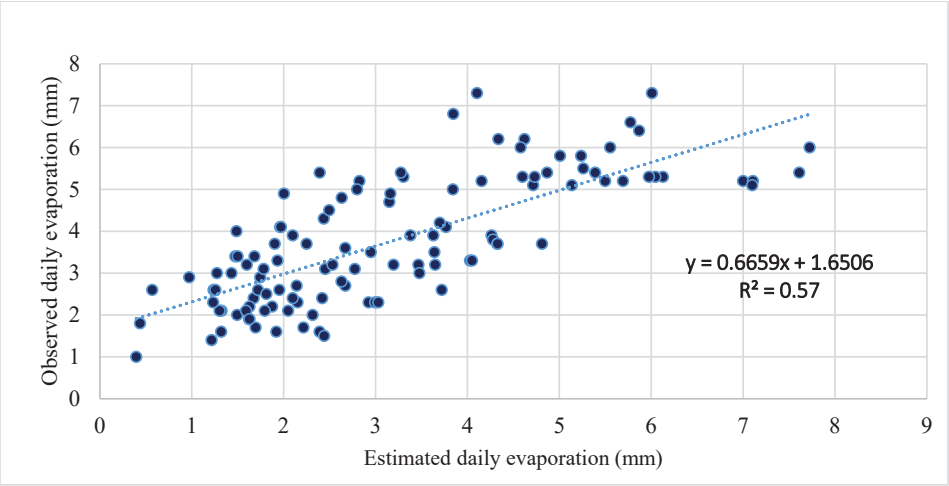

Fig. 5: Assessment of evaporation estimates using measurements of an ultrasonic sensor over an experimental irrigation pond via regression.

Table 3: Descriptive statistics on the agreement between observed water level measurements and evaporation estimates from open-access datasets

Statistic	Min.	Max.	Mean	SD	R *	MAE	RMSE
Observed daily evaporation based on water level readings (mm)	0.4	7.72	3.15	1.8	0.75	1.02	1.27
Corresponding open-access datasets of daily evaporation (mm)	1	7.3	3.76	1.49			

*p-value < 0.05, confidence Interval = 95%

amount of water lost to evaporation on a monthly basis, whereas the orange bars depict the overall water was lost from the pond. The vertical lines on the data points represent error bars, showing uncertainty or variation in the measurements based on validation results.

Across all three years, evaporation increases during the summer months (June to September), with the highest levels usually in July or August. For example, in 2023, evaporation peaked at over 220 mm/month in July and August, which caused a large increase in water loss, reaching nearly 4500 m^3 by the end of September. A similar trend is observed in 2022 and 2021, where increased summer evaporation leads to greater water loss. In cooler months like November and December, evaporation drops below 100 mm/month, and water loss from the pond would also become much lower. However, ponds were not reportedly filled completely outside the irrigation season (May-September). For all the open ponds visited in this study, the total water loss would amount to 40,500 m^3/year. Given an estimated 240 ponds in the north Badia, the total would amount to over 1 million m^3/year. In contrast to other regions, where more than 10 billion m^3 of water losses due to evaporation from open ponds are documented, these losses may seem insignificant (El-Shirbeny and Abutaleb, 2018). These losses may also be small compared to other sources of non-beneficial like over-irrigation, which could exceed 30% of water consumption (Abdelmoneim *et al.,* 2024). However, considering Jordan's severe water scarcity, these losses have a considerable impact on sustainability in the Jordanian sector. The entire water abstraction in the Jordanian Badia is around 120 million m^3 of water, which means that evaporation losses would account for nearly 1% of the Badia's water consumption (Al-Bakri *et al.,* 2023). These outcomes hold great significance when reflecting on water conservation in Jordan, a country that is already grappling with serious water shortages. Furthermore, climate projections downscaled to the study area has shown that evaporation will likely increase by around 5% by 2030 (Al Qatarneh *et al.,* 2018). These results highlight the significance of

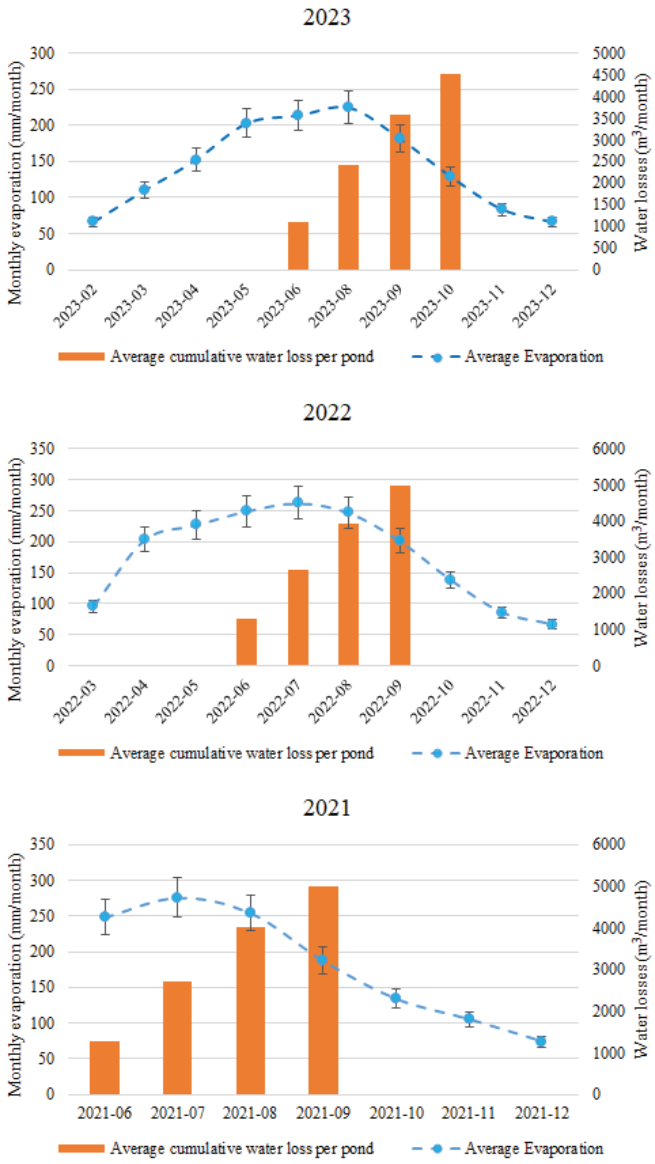

Fig. 6: Average monthly evaporation across the study region and the cumulative average volume of water losses from a single open irrigation pond

reducing the restrictions on farmers to adopt better water-saving practices, such as plastic covers, floating covers, or switching to underground water storage. These easy-to-implement solutions can effectively decrease evaporation and aid in preserving essential water, especially in the scorching and dry summer season when crops are in greatest need. Efficient water management is key to improving irrigation and protecting Jordan's limited water resources.

Energy and carbon implications

Through the observation that irrigation ponds were consistently filled to their maximum and by calculating the atmospheric water loss, it was possible to estimate the energy consumption that resulted from this. This required some inputs related to the water pumping capacity. Water levels were generally very deep in the study region, ranging between 350 m and 500 m depths, but 400 m was deemed to be a representative

number for most sites. The water sources were 600m away from ponds on average and most farmers had one to three 90-degree elbow fitting (bends). Based on this information collected during the visits, a TDH value of 420m was assigned to calculate energy consumption. The operational status of the pumps was maintained, although their conditions were not ideal; an assessment of the pumps' specifications, models, and age was performed to gauge their efficiencies. Accordingly, the average value for η was estimated at 70% based on expert judgement by the field team. These values were used to estimate the SEC of 1.635 kWh/m^3, i.e. the amount of energy needed to deliver 1 m^3 of water from the source to the pond. Given SEC and the volume of water pumped to compensate evaporation losses, the total energy consumption was estimated (Fig. 7). The findings indicate that approximately 2000 kWh were utilized per pond within a specific year. For a total of 9 ponds visited in this study, this amounted to 18000 kWh. The carbon footprint was determined based on the emission factor for the national grid in Jordan, which was 0.5425 kilograms (kg) of CO_2e per kWh. Diesel-powered pumps were not considered due to being very few and likely to be replaced soon. An estimation of the carbon footprint for solar-powered pumps was not conducted, as the primary emphasis was placed on water pumping to offset evaporation losses rather than evaluating the entire system. The results demonstrate that compensating water losses from just one pond corresponded to up to 1.2 tons of CO_2e every year. Given that around 240 ponds exist in the Badia region, and an estimated 70% of farmers relying on non-renewable energy sources, the annual carbon footprint would amount to nearly 200 tons of CO_2e. The resources allocated to offset evaporation losses do not directly enhance crop biomass, which would consequently lead to a notable decrease in the overall water efficiency of the farm. It was not possible to precisely determine the amounts of water beneficially used for crop production on each farm, but the resulting water losses would certainly impact water productivity negatively. This situation clearly highlights a serious inefficiency in water and energy use. Moreover, water lost through evaporation reduces overall water efficiency and contributes to greenhouse gas emissions, which is a significant concern in relation to climate change. While the aspect of water losses has been discussed by previous researchers (Abdelal, 2021; Elsebaie *et al.,* 2017), this work demonstrate that the issue expands well beyond water losses. Evaporation losses from ponds, in the context of agricultural water use, are evidently linked to high amounts of unnecessary carbon emissions and energy consumption. This highlights how tackling this challenge can play a crucial role in promoting sustainable farming, particularly in water-scarce regions like Jordan.

This highlights how this challenge is directly linked to several United Nations Sustainable Development Goals (SDGs). Most notably, it affects SDG 6: Clean Water and Sanitation, which emphasizes the need for efficient water use and reducing water losses in agriculture. Limiting evaporation from irrigation ponds aids in achieving Target 6.4, which focuses on greatly improving water-use efficiency across various sectors. The issue also contributes to SDG 13: Climate Action, since avoidable energy use for water pumping leads to unnecessary greenhouse gas emissions. In addition, smarter water and energy use aligns with SDG 12: Responsible Consumption and Production, promoting the sustainable use of natural resources. The technique for modeling and projecting the water-carbon costs across a range of meteorological and operational scenarios can be performed as outlined in this study. This requires the following information:

1) the dimensions and surface area susceptible to atmospheric water losses;

2) the management practices, e.g. periods of storage usage, filling capacity;

3) measurements, projections, and estimations of evaporation;

4) water system information, i.e. the operational condition and capacity of local pumps;

5) layout of the water delivery system, e.g. distance from the water source, number of bends or elbow fittings;

6) the energy source for the water delivery system;

7) the carbon equivalent factor for the corresponding energy sources.

Following the collection of this information, modeling the carbon footprint resulting from compensating evaporation losses can be estimated, using Eq. 6 (Abdelal *et al.,* 2024; Abdelal, 2021):

$$CO_2e = Surface\,area \times Evaporation \times \frac{\rho \times g \times TDH}{\eta \times 3.6 \times 10^6} \times carbon\,equivalent\ factor \quad (6)$$

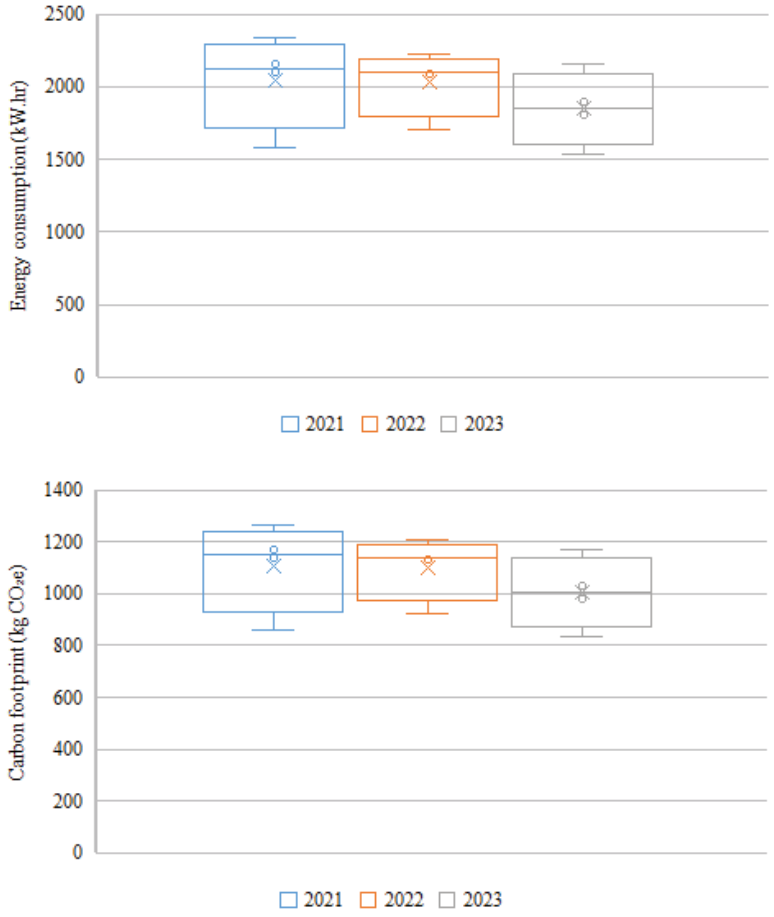

Fig. 7: Energy and carbon implications of supplementing atmospheric water losses in open irrigation ponds

Eq. 6 was devised based on Eqs. 1 to 3, and it can help simulate the impact of water-level changes or climate-projections of evaporation using downscaled data.

Economic costs and viability

Open irrigation ponds in the north Badia lose on average 4500 m³ of water per year and require nearly 2000 kWh of energy to replenish those losses. At a local water price of $0.06/m³ and an energy cost of $0.08/kWh, annual direct costs per pond amount to $430 per pond. This totals $3870 each year across the nine monitored ponds. In the region, over $100,000 is allocated annually just for replacing water lost to evaporation in approximately 240 ponds. This finding indicates that even when water prices are subsidized, the economic impact of evaporation can be substantial. According to Abdelal *et al.* (2021) Floating photovoltaic (PV) panels installed over the pond can reduce evaporation by around 60% and generate electricity. For a typical 5000 m² pond, at $70/m², installation costs would amount to $350,000. Evaporation reduction yields annual savings of 2700 m³ of water ($162) plus 1200 kWh of energy ($96), or $258 per year, implying a simple payback of 1356 years on irrigation-efficiency grounds alone. Additionally, monetizing the electricity generated, either via direct consumption or feed-in tariffs, can substantially benefit this process, but it demands in-depth knowledge of farmers' water and energy consumption patterns. Constructing underground tanks also has the same issue of very large initial investment. The payback from evaporation elimination would not justify the investment, and

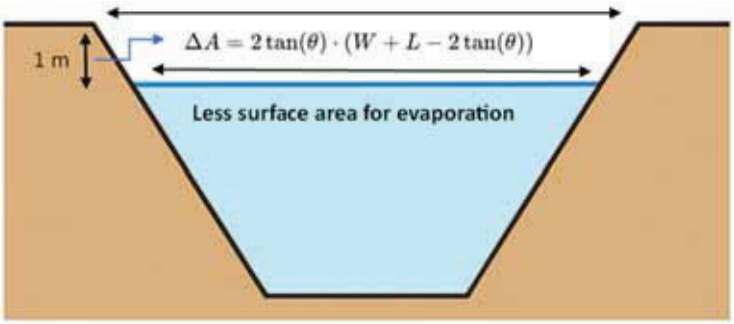

Fig. 8: An illustration showing how dropping the water level by 1 m reduces the surface area of evaporation based on a trigonometry equation derived in this study

there are no other cost reduction aspects from this option. By physically blocking the water-air interface, shade balls contribute to a reduction in evaporation of ~60%. Covering a 5000 m² pond at 0.04 m² per ball requires about 125000 balls. Under today's local price of $1/ball, the material cost is $125000, with a payback period near 484 years. If unit cost falls to $0.50, payback shortens to 242 years; at $0.10, to 48 years. Partial-coverage schemes, bulk procurement, or local manufacture could drive the unit price down toward these more attractive thresholds. A no-capital-cost approach is to lower the fill level instead of keeping the pond filled to the brim. Decreasing the water level can lead to a reduction in the surface area exposed to the atmosphere, as a result of the trapezoidal configuration of the ponds (Fig. 8). The effect of dropping the water level on surface area can be derived using simple geometry. Dropping the water level by 1 m reduces the surface area exposed to evaporation by about 296 m². Given an average annual evaporation depth equivalent to the full-pond loss, a 1 m drop saves roughly 260 m³ of water and 425 kWh of pumping energy each year. At existing rates, this amounts to $49.60 in savings on water and energy, accomplished just by functioning at a slightly shallower depth, with no initial investment required. At least 4 farmers who were recommended this approach did adhere to it, this was confirmed during the secondary visits to the farm sites.

This strategy lowers the volume of water held in storage. To reduce risk, farmers need to improve the efficiency of their irrigation water use. One of the methods this can be achieved is by resorting to sensor-based irrigation which can reduce water use in irrigation by up to 35% at a low cost (Abdelmoneim *et al.,* 2024). Earlier studies conducted in the Jordanian Badia has proposed that irrigation water consumption could be minimized without negatively affecting crop yields (Amdar *et al.,* 2025). When irrigation requirement is reduced, then less water can be stored without any additional risk in case of water supply issues. None of the advanced covers provide quick returns solely based on water-energy savings; however, integrating various strategies can shift the balance through the following actions:

- Fostering and providing financial assistance for advanced irrigation tools (like soil moisture sensors or weather monitoring stations) to decrease water consumption;
- Suggesting reducing pond depth by 1 m through extension services to capture an immediate $50 in savings per meter dropped. This was notable acceptable to farmers who participated in this study;
- Piloting shading balls at reduced unit costs (≤ $0.10) to recover more evaporation savings per dollar;
- Integrate PV covers in areas where solar revenue can alleviate installation costs through electricity sales or on-farm utilization. This may involve training extension services on the cost-benefit analysis of renewable energy systems to aid farmers in their choices;
- Provision of subsidies and regulatory support for pond-covering materials and integrated solar-water systems.

The experience from previous efforts in Jordan shows that piloting interventions can lead to other farmers following by example, based on the old term 'seeing is believing'. This is truly how fertigation systems rose to prominence in Jordan. By piloting and gradually adopting these methods, farmers

and policymakers can effectively minimize yearly evaporation losses for each pond. It would be essential to layer these options, starting with the zero-cost water-level adjustment and then targeting cost-effective shade solutions. Implementing this can preserve the limited water supply and mitigate unnecessary energy usage and carbon emissions in the water-stressed agricultural sector of Jordan.

CONCLUSION

Evaporation losses from open ponds are one of the major sources of non-beneficial agricultural water use around the world. Nonetheless, there is a shortfall of studies investigating the magnitude of this problem in areas that utilize conservative water management practices and their associated energy and environmental consequences. This study explored the factors and implications of agricultural water storage using open-ponds in the north Jordanian Badia, one of the most water scarce regions in the world. This study utilized field surveys and measurements of pond areas, field assessments of irrigation systems, open-access meteorological data, and sensor-based validations. The findings indicated that open ponds are a common feature in the area, primarily because they are easy to build, cost-effective, and can serve as a backup water source during pump malfunctions or when there are issues with water availability. The results demonstrated that around 45,000 m^3 of water were lost from each pond on average every year. This lost water was compensated mainly by pumping from groundwater, most commonly using energy from the national grid. This was estimated to account for over 1 million m^3 of water pumped and over $100,000 spent annually just to replace evaporated water across the Badia region. The most significant losses were observed during the peak evaporation months of July and August annually. The analysis in this study showed that compensating this evaporation loss from just one pond can lead to up to 2000 kWh of energy use every year. This resulted in around 1.2 tons of carbon emissions per pond, and an estimated 200 tons of CO_2e every year across the Jordanian Badia region. The study indicated that while farmers acknowledged evaporation losses, they lacked a full understanding of the financial implications regarding water, energy, and money. Many farmers reported interest in reducing these losses, but faced several obstacles. Covering ponds with plastic or shading balls was reportedly expensive and not simple to install. A number of farmers were concerned that it might affect water quality or complicate daily usage. Others said local suppliers and contractors were not available or were too expensive. In this study, the cost-benefit analysis indicated that physical covers, including shading balls and floating solar panels, offered a meager return on investment. This was specifically when accounting only for the benefits of minimizing the losses from evaporation, excluding other benefits. This was likely related to subsidized water prices for farmers in Jordan. Another approach to consider was to reduce the water level in ponds, which would minimize the surface area in contact with the atmosphere, thereby avoiding costs, and this suggestion was well accepted by many farmers. This option provides a modest reduction in evaporation losses, but provides the advantage of requiring no capital investment. It is, however, necessary to optimize water consumption through soil sensors or meteorological stations to make sure that reduced water storage would not account for any risks from supply issues. Conducting pilot site tests, combined with a phased and structured implementation of possible solutions and subsidized alternatives, can lead to a successful reduction in water, energy, and environmental expenses. Collaboration between farmers and policy makers is required, as the current policy of mandating permits on these ponds is not likely to minimize the negative impacts. This is due to the necessity and convenience of these ponds to farmers. Eliminating barriers to renewable energy and pond-covering licenses would also contribute positively. Capacity building on the use of open-access data sources can also minimize the issue of data availability for assessment, as demonstrated in this study. These upgrades would lead to water conservation, reduced energy usage, and a reduction in carbon emissions, resulting in a more sustainable farming practice in the region overall, and would additionally aid in achieving broader goals. Saving water helps Jordan achieve its national goals for agriculture and water security. It also supports global sustainability goals, such as SDG 6 on clean water, SDG 13 on climate action, and SDG 12 on responsible consumption.

AUTHOR CONTRIBUTIONS

A. Al-Khreisat supervised the manuscript

preparation and data analysis. Q. Abdelal performed the validation and meteorological data analysis. M.R. Al-Kilani helped prepare the first draft and supervised data collection and performed data analysis. J. Al-Bakri performed the visualization and supervised the project. I. Damra performed the field measurements and assisted in data collection. O. Al-Kilani assisted in the field work and data collection. All authors read and approved the final manuscript.

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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.

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ABBREVIATIONS

%	Percent
$	United states dollar
η	Pump efficiency
ρ	Water density
x_i	Measurement of evaporation data point
y_i	Estimation of evaporation data point
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
ET	Evapotranspiration
g	Gravitational acceleration
ha	Hectare
h	Hour
kg	Kilogram
kW	Kilo watt
m	Meter
m^2	Squared meter
m^3	Cubic meter
MAE	Mean absolute error
mm	Millimeter
R	Pearson's correlation coefficient
RMSE	Root mean squared error
SDG	Sustainable development goals
SEC	Specific energy consumption

SD	Standard deviation
TDH	Total dynamic head
WaPOR	Water productivity portal

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ORIGINAL RESEARCH ARTICLE

Economic prosperity and ecological sustainability strategy for fishing violations hotspots

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ABSTRACT

BACKGROUND AND OBJECTIVES: Illegal, unreported, and unregulated fishing threatens Indonesia's marine biodiversity, economic security, and governance, causing estimated annual losses of 1.85 billion United States dollar. In spite of improvements in monitoring, there are still considerable enforcement gaps, especially in remote and ecologically significant waters like the Arafura, Natuna, and Java Seas. The purpose of this study was to merge the spatial-temporal persistence of fishing violations with economic valuation to detect high-risk hotspots and to direct targeted fisheries enforcement initiatives.

METHODS: A total of 77,678,937 vessel monitoring system records from October 2021 to July 2024 were analyzed on a 0.25-degree spatial grid and grouped monthly. Statistically significant hotspot areas were identified using a spatial clustering analysis with an eight-nearest-neighbor configuration. A persistence index was subsequently utilized to assess the percentage of months during which each grid cell retained hotspot status throughout the 39-month observation period. The economic importance of each cell was assessed through landed catch values, which were normalized and integrated with the persistence measure to generate a composite patrol priority score.

FINDINGS: There were two violations: the vessel monitoring system was turned off for more than 24 hours, and the notice of sailing certificate was incomplete, which together represented over 92 percent of legitimate national cases. Spatial analysis identified 21 high-risk clusters, concentrated in the Java, Natuna, and Arafura Seas, representing over 85 percent of top-decile hotspots. These areas persisted for more than 80 percent of the study period and overlapped with zones of highest cumulative landed value (~78 billion United States Dollars). Violation-specific mapping revealed distinct patterns: conservation zone incursions in eastern Indonesia, licensing violations in Papua and Maluku, and boundary-related offenses in smaller scattered clusters.

CONCLUSION: Combining environmental durability with economic valuation shows that a small segment of Indonesia's territorial waters and exclusive economic zone is responsible for a large portion of the risks linked to illegal and unregulated fishing. Prioritizing enforcement in these zones—supported by advanced satellite monitoring, predictive analytics, and community-based surveillance can enhance compliance, reduce operational costs, and safeguard ecologically and economically critical waters. The framework provides a robust decision-support tool for the Ministry of Marine Affairs and Fisheries and various enforcement, facilitating improved targeted interventions for sustainable fisheries governance.

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INTRODUCTION

Indonesia, an extensive archipelago of more than 17,000 islands, possesses rich and diverse marine resources that are central to both its economic prosperity and ecological sustainability. Nonetheless, these resources are experiencing heightened pressures due to human activities, as illegal, unreported, and unregulated (IUU) fishing persists as one of the most critical threats to both maritime security and resource sustainability. Globally, IUU fishing causes estimated losses of United States Dollars (USD) 10–23 billion each year, undermining lawful fisheries, reducing government revenues, and jeopardizing the livelihoods of coastal communities (Temple *et al.,* 2022; Ford *et al.,* 2018). Indonesia, with its vast territorial waters, rich biodiversity, and one of the world's largest exclusive economic zones (EEZs), is particularly vulnerable, suffering estimated annual losses of around 1.86 Billion United States dollar (USD) from such activities (Ali *et al.,* 2020; Khan *et al.,* 2024). The Ministry of Marine Affairs and Fisheries (MMAF) has identified the surveillance and sustainable management of marine and fisheries resources as one of its five strategic priorities (Trenggono *et al.,* 2025; Tri Yuwono *et al.,* 2025; Sahami *et al.,* 2024). Nevertheless, in spite of persistent enforcement initiatives, illegal, unreported, and unregulated (IUU) fishing still undermines ecological resilience, intensifies social disparities, and diminishes the trustworthiness of state maritime enforcement agencies (Lestari *et al.,* 2020; Suhaidi *et al.,* 2022; Wibowo *et al.,* 2023). While the Indonesian government has taken significant steps to combat IUU fishing—including the establishment of Task Force 115 in 2015 and the adoption of stricter vessel monitoring regulations—enforcement gaps remain substantial, particularly in remote maritime zones such as the Arafura Sea, Sulawesi Sea, and Natuna Sea (Suherman *et al.,* 2020; Merdekawati *et al.,* 2021). These regions are defined by expansive fishing territories, insufficient patrol presence, and significant operational costs, rendering them continual hotspots for illegal operations (Ford *et al.,* 2018; Rahmadani *et al.,* 2020; Wibowo *et al.,* 2023; Go *et al.,* 2024). The MMAF, as the primary enforcement authority, continues to face logistical and technological challenges in ensuring effective surveillance over such an expansive maritime jurisdiction, despite advancements in vessel monitoring systems (VMS) and automatic identification system (AIS)-based analytics (Ford *et al.,* 2018; Khan *et al.,* 2024; Islam and Hasan, 2024). Although operational gaps are significant, the ongoing issues of IUU fishing in Indonesia are further exacerbated by fragmented legal and institutional frameworks. Overlapping mandates between the Ministry of Marine Affairs and Fisheries (MMAF), the Coast Guard (Bakamla), and the Water Police (Polairud) often blur enforcement authority, resulting in duplicated patrol efforts and inconsistent sanctioning. The disunity among institutions produces inefficiencies that weaken the effectiveness of policy implementation and enforcement results (Samiaji, 2015). Strengthening harmonized legal frameworks, joint command structures, and integrated enforcement protocols is therefore essential to promote more coherent and consistent compliance. At the international level, Regional Fisheries Management Organizations (RFMOs) such as the Western and Central Pacific Fisheries Commission (WCPFC), Indian Ocean Tuna Commission (IOTC), and Commission for the Conservation of Southern Bluefin Tuna (CCSBT), along with global agreements including the FAO Port State Measures Agreement (PSMA) and the WTO Fisheries Subsidies Agreement, provide important frameworks to address IUU fishing. Indonesia is actively involved in these mechanisms; nonetheless, it encounters challenges, especially in data-sharing, coordinated sanctioning, and the alignment of national monitoring systems with RFMO databases. These limitations stem from insufficient institutional capacity and fragmented coordination structures. Enhancing established coordination and building capacity is crucial for fully achieving the operational advantages of these international commitments (Jaya, 2024). Cross-border cooperation with neighbouring countries is equally important, as many high-risk violations occur near maritime boundaries in the Natuna, Sulawesi, and Arafura Seas. Indonesia has engaged in initiatives such as the Trilateral Maritime Patrols with Malaysia and the Philippines, and bilateral fisheries cooperation with Papua New Guinea and Timor-Leste. However, these efforts remain largely ad hoc and reactive. Embedding joint patrols, intelligence-sharing, and command centers into established and enduring cooperative frameworks is essential for enhancing deterrence and maintaining consistent enforcement in transboundary

waters (Uno *et al.,* 2017). Political economy challenges also complicate enforcement efforts. Indonesia is still in the process of strengthening governance systems to reduce risks of rent-seeking, accountability gaps, and inconsistent sanctioning, all of which can weaken deterrence and distort enforcement priorities. Studies highlight that corruption and fragmented authority remain persistent barriers to effective fisheries governance. Reforms that prioritize transparent licensing, the broader application of digital monitoring technologies like vessel monitoring systems (VMS), and ongoing legal follow-up are vital to enhance accountability mechanisms and support more sustainable law enforcement (Rahmawati *et al.,* 2025). In addition, socioeconomic drivers at the community level play an important role. Small-scale fishers facing poverty, limited credit access, and a lack of alternative livelihoods may perceive regulatory restrictions as immediate threats to their income security, prompting risky or unregulated practices. Studies indicate that numerous livelihood enhancement initiatives in Indonesian fishing communities have faced challenges in adequately meeting the financial and human capital requirements of impoverished fishers, especially laborers' and small-scale boat operators. These groups often require more than physical capital—they need targeted support in skills training, microfinance, and economic diversification opportunities (Stanford *et al.,* 2014). Initiatives like aquaculture development, skills training, and infrastructure projects such as the Kampung Nelayan Modern (KALAMO) program—which improves post-harvest facilities and market access—can help reduce vulnerability and create stronger incentives for compliance. Finally, reducing IUU fishing offers significant economic gains. With national losses estimated at USD 1.86 billion annually, even a conservative 10–20% reduction in persistent hotspots could recover USD 156–312 million each year. When integrated with fisheries sector multipliers, this recovery could lead to a total economic impact ranging from USD 200 million to 580 million, support numerous jobs across the value chain, and boost state revenues from both tax and non-tax sources. In high-value tuna and shrimp fisheries, stronger compliance not only prevents stock depletion but also enhances access to premium export markets like Japan and the European Union, where traceability and sustainability standards are stringent (Khan *et al.,* 2024). These advantages additionally validate the focus on enforcement in high-value zones. Currently, the existing body of work on IUU fishing in Indonesia has largely concentrated on legal frameworks, policy reforms, and aggregate national loss estimates (Merdekawati *et al.,* 2021; Suherman *et al.,* 2020; Islam and Hasan, 2024). However, there remains a critical gap in integrating spatial–temporal analysis of persistent fishing violations with their associated economic impacts. While some studies highlight the spatial clustering of illegal activities (Ford *et al.,* 2018; Rahmadani *et al.,* 2020), few have examined the recurrent nature of these violations over time or explicitly linked them to high-value fisheries—areas where economic losses from illegal activities are most severe. In the absence of such integration, enforcement strategies may become reactive and scattered, leading to a dilution of limited resources instead of focusing them on the areas with the highest risk (Ford *et al.,* 2018; Khan *et al.,* 2024; Wibowo *et al.,* 2023). This study fills existing gaps by utilizing the Getis-Ord Gi* hotspot analysis method (Zhang *et al.,* 2024) to analyse over 77 million VMS records collected between October 2021 and July 2024, aiming to detect consistent spatial and temporal patterns of violations within Indonesia's territorial and EEZ waters. It also incorporates landed catch values to evaluate the economic intensity of these hotspots, generating a composite risk score that merges persistence with potential economic loss. The results indicate specific high-risk areas—particularly in the Java Sea, Natuna Sea, Sulawesi Sea, and Arafura Sea—where focused enforcement efforts could lead to significant improvements in compliance and economic advantages. By combining spatial persistence with economic metrics, this study provides an evidence-based framework to support the MMAF and other maritime enforcement agencies in prioritizing patrol resources, enhancing surveillance efficiency, and informing policy measures aimed at sustainable fisheries management in Indonesia and beyond. Platforms like global fishing watch have leveraged AIS and VMS data to reveal the movements of distant-water fleets (Kroodsma *et al.,* 2022), while studies in West Africa and Southern Africa have demonstrated how synthetic aperture radar (SAR) and night-time imagery can detect unreported vessels in remote waters (Kurekin *et al.,* 2019; Mdakane, 2022). These international examples underscore the

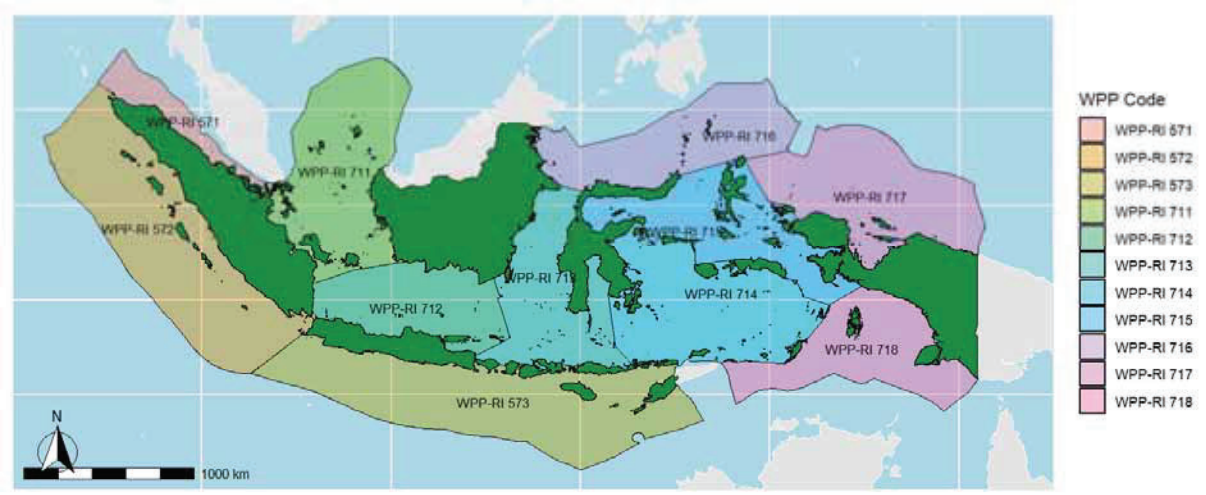

Fig. 1: Geographic location of the study area within multiple Indonesian Fisheries Management Areas (FMAs/WPPs)

advantages and constraints of satellite surveillance—such as coverage gaps and blind spots for small-scale fleets—and inform the approach in Indonesia, where the spatial persistence and economic intensity have been incorporated into a customized patrol prioritization framework. The aims of this study are to integrate spatial–temporal persistence of fishing violations with economic valuation to identify high-risk hotspots and guide targeted fisheries enforcement. Satellite-based monitoring systems are becoming more prevalent for tracking fishing activities and supporting global enforcement initiatives. The study was conducted within Indonesia's territorial and exclusive economic zone waters between 2022 and 2024.

MATERIALS AND METHODS

Study area

The analysis focused on the Republic of Indonesia's EEZ and territorial waters, spanning from 92° east (E) to 142°E longitude and −12° to 10° latitude. Indonesia's waters encompass multiple fisheries management zones Wilayah Pengelolaan Perikanan (WPP), Marine Protected Areas (MPAs), and sensitive ecological regions.

Data sources

Vessel monitoring records were obtained from the MMAF, encompassing a comprehensive dataset of 77,678,937 position reports collected between October 2021 and July 2024. Each record contained detailed information, including vessel position (latitude and longitude), timestamp, speed, heading, vessel attributes, and binary indicators for specific fishing violations. These infractions included fishing beyond the authorized route, lack of a fishing vessel fitness certificate (SLO), violations of designated fishing areas (DPI), unauthorized entry into conservation zones, deactivation of the VMS for over 24 hours, absence of a sailing notice (SPB), and possessing an expired fishing license (SIPI/SIKPI). In addition to the operational data, economic information was recorded, detailing landed catch species and weight, total catch in kilograms, and the corresponding catch value in USD. VMS was selected as the primary dataset because it is mandatory for licensed fishing vessels and provides consistent administrative coverage. However, it is not fully tamper-resistant, as transponders can be intentionally disabled, unlike AIS or SAR which can offer complementary detection. A hybrid monitoring strategy that integrates VMS with AIS validation and SAR imagery would enhance the reliability of surveillance and support future modernization investments.

Spatial aggregation

A uniform spatial grid with a resolution of 0.25°, approximately 27.8 kilometers (km) at the equato, was overlaid across the study area to enable systematic spatial aggregation. Each vessel observation was assigned to a grid cell based on its central coordinates. The analysis used a 0.25° grid resolution to balance

spatial detail with data reliability and computational efficiency. While finer resolutions may capture sub-hotspot variation, they often introduce noise due to sparse VMS coverage—especially in small-scale fisheries. This resolution is extensively utilized in the monitoring of global fisheries because it offers adequate event density for thorough spatial and economic analysis (Kroodsma *et al.,* 2018; Watson and Haynie, 2018), thus making it appropriate for national enforcement planning. Temporal aggregation was achieved by grouping records into monthly bins, with timestamps floored to the first day of each month using the floor-date function from the lubridate package in R (Grolemund and Wickham, 2011; R Core Team, 2024). The sum of violation events was determined for each grid cell and month, categorized by violation type. This spatial-temporal gridding approach aligns with established fisheries monitoring and enforcement analyses, which have demonstrated its utility in detecting spatial clusters and identifying persistent patterns of illegal fishing activity (Ford *et al.,* 2018; Temple *et al.,* 2022; Doherty *et al.,* 2021).

Local hotspot detection

To identify statistically significant spatial clusters of fishing violations, the local Getis-Ord Gi* statistic was computed for each month and violation type using the SPDEP package in R, a widely used tool for spatial data analysis, particularly focused on modeling spatial dependence and spatial autocorrelation in geographic data (Bivand *et al.,* 2013; R Core Team, 2024). Neighbour relationships were defined using a *k*-nearest neighbours approach (*k* = 8) with self-inclusion to meet the Gi* definition requirements (Getis and Ord, 1992; Ord and Getis, 1995). Row-standardized spatial weights (style = "W") were applied to ensure comparability of statistics across the study area. The Gi* Z-score is calculated using Eq. 1 (Anselin, 1995):

$$Gi_i^* = \frac{\sum_j w_{ij}x_j - \bar{X}\sum_j w_{ij}}{S\sqrt{\frac{n\sum_j w_{ij}^2 - (\sum_j w_{ij})^2}{n-1}}} \quad (1)$$

Where, xj is the violation count in cell j, wij is the spatial weight between cells i and j, n is the number of cells, X^- is the mean violation count, and S is the standard deviation. Cells with Gi ≥ 1.96 were considered hotspots significant at the 95 percent (%) confidence level; those with Gi ≤ -1.96 were considered cold spots (Getis and Ord, 1992; Ford *et al.,* 2018). In this study, both 95% and 99% statistical confidence thresholds were applied to identify hotspots using the Getis-Ord Gi* statistic. The 99% threshold highlights the most persistent and intense hotspots with the highest certainty, suitable for prioritizing limited enforcement resources. Concurrently, the 95% threshold provides for the inclusion of secondary hotspots that may still hold operational relevance, particularly in dynamic or border areas where enforcement is less often observed. Comparing both thresholds provides a more nuanced enforcement map, distinguishing between "core" high-certainty hotspots and "emerging" or peripheral hotspots that warrant monitoring.

Persistence index

For each grid cell g and violation type t, a persistence index was calculated (Eq. 2), representing the proportion of months a cell was classified as a statistically significant hotspot during the 39-month observation period. The persistence index was calculated as the proportion of months in which a cell was identified as a statistically significant hotspot (Gi* ≥ 95%). Months without VMS data were omitted from the denominator to avoid skewing the persistence scores downward. For borderline Gi* values, only those meeting or exceeding the 95% threshold were classified as hotspot months, ensuring consistency and avoiding subjective interpretation. In situations where there are ties between neighboring cells, persistence values were documented separately for each cell, since the analysis was conducted on a grid basis instead of being spatially aggregated. This approach ensures that persistence reflects robust temporal recurrence without bias from missing data or arbitrary thresholding. This metric captures the temporal consistency of violations, allowing differentiation between isolated events and areas of recurrent non-compliance. This study employs the persistence index retrospectively; however, the same concept could be beneficial for predictive applications. Machine learning models trained on temporal persistence, vessel attributes, and environmental factors might predict high-risk violations prior to their occurrence. Accuracy would depend on addressing data gaps (e.g., limited coverage of small vessels) and minimizing reporting biases, but hybrid predictive

Table 1: National and hotspot-level distribution of fisheries violations (Gi, k = 8, 95% CI)

No.	Violation type	total	Number of valid data (N valid)	Valid (%)	persentage_ of_total (%)	N_hotspot (p>0.01)
1	Turning off VMS > 24 hours	28.928.303	60.821.515	47.48	37.24	794.759
2	Entering conservation zone	3.210.150	60.821.515	5.27	4.13	51.946
3	Incomplete notice of sailing certificate (SPB)	34.482.743	60.821.515	56.6	44.39	856.336
4	Expired fishing vessel fitness certificate (SLO)	2.088.314	60.821.515	3.43	2.69	73.114
5	Expired fishing license	2.707.384	60.821.515	4.44	3.49	38.051
6	fishing area violation	332.584	60.821.515	0.55	0.43	2.218
7	Fishing outside permitted route	396.316	60.821.515	0.65	0.51	12,749

approaches could enable more proactive and cost-efficient enforcement planning. For each grid cell *g* and violation type *t*, a persistence index was calculated, using Eq. 2 (Getis and Ord, 1992):

$$\text{Persistence}_{g,t} = \frac{\#\{\text{months } m : Gi^*_{g,t,m} \geq 1.96\}}{\text{Total months in study}} \times 100\% \quad (2)$$

This metric indicates the percentage of months during which a cell was identified as a significant hotspot. While this study applies retrospective hotspot analysis, emerging machine learning methods could forecast high-risk violations by combining vessel behavior, temporal persistence, and environmental data. The accuracy of predictions is still constrained by data deficiencies (for instance, the underrepresentation of smaller vessels) and biases in reporting; however, these methods show potential for proactive enforcement. Incorporating multi-source data would further improve reliability while minimizing the risk of reinforcing existing biases.

Economic intensity

Economic intensity per grid cell was derived by summing total catch value in USD for all vessel events located in that cell over the study period, using Eq. 3 (Jin *et al.,* 2013):

$$E_g = \sum_{k \in g} \text{total_idr}_k \quad (3)$$

Composite risk score

A composite patrol priority score was computed by combining normalized persistence and normalized economic intensity, using Eq. 4 (Jin *et al.,* 2013). This risk-focused framework additionally offers a basis for evaluating modernization alternatives. While it is technically possible to integrate real-time satellite imagery, drones, and acoustic monitoring with patrol operations, the adoption is hindered by financial, technical, and regulatory limitations. A phased approach that applies these tools first to high-priority hotspots would maximize cost-effectiveness and enable gradual capacity-building without overstretching enforcement systems. A composite patrol priority score is calculated as follow:

$$\text{Risk}_g = \text{scale}(\text{Persistence}_{g,any}) \times \text{scale}(\log(1 + E_g)) \quad (4)$$

Where, the scale represents min–max normalization to the range [0,1].

RESULTS AND DISCUSSION

Number of violations

Out of 77,678,937 total observations, 60,821,515 records—or 78.2% of the dataset—were deemed valid for further processing to detect and classify marine and fisheries violations in Indonesia (Table 1). The analysis compared the total number of recorded incidents nationwide with the subset occurring within statistically significant spatial hotspots, identified using the Getis-Ord Gi* statistic (k = 8 nearest neighbors, 95% confidence level, z > 1.96). Essentially, the dataset is marked by two significant violation types—Turning Off VMS for a period greater than 24 hours and incomplete SPB. Together, they account for more than 92% of all valid violations nationally (28.93 million and

34.48 million cases, respectively) and represent the highest counts within hotspots (794,759 and 856,336 cases, respectively). Infrequent violations display recognizable spatial characteristics. For example, entering conservation zones accounts for 3.21 million valid cases (5.27% of total valid records) with 51,946 occurring in hotspots, while expired SLO and expired fishing license contribute 2.09 million (3.43%) and 2.71 million (4.44%) valid cases, respectively, with hotspot counts of 73,114 and 38,051. The least frequent violations—fishing area violation (332,584 cases; 0.55%) and fishing outside the permitted route (396,316 cases; 0.65%)—are rare at the national scale but exhibit notable spatial clustering, with 2,218 and 12,749 cases occurring in hotspots, respectively. This pattern reveals that although these offenses are not common, they are often found in particular areas, probably close to maritime borders or in regions with specific fishing prospects. These results highlight that enforcement strategies should not only address the most prevalent violations but also prioritize geographically concentrated, high-impact offenses that could have disproportionate ecological and economic consequences.

The distribution of the number of violation types per record, as shown below in Fig. 2, reveals that the majority of records involve singular or dual violation types. Specifically, 43.1% of records contain only one type of violation, followed by 30.3% with two types, and 21.7% with no recorded violations. Instances of multiple violations are relatively rare, with only 3.8% of records showing four or more types of violations, and just 1.0% having precisely three types. This pattern indicates that while isolated or paired violations dominate the dataset, a non-negligible fraction of cases involves multiple concurrent violations, suggesting potential clusters of non-compliance that may require more comprehensive enforcement and monitoring strategies.

Persistence hotspots

The Getis-Ord Gi* statistic on a 0.25° spatial grid, using a k-nearest neighbor (k=8) configuration, has been applied to identify statistically significant clusters of high activity (hotspots) and low activity (coldspots) across Indonesian waters. The analysis

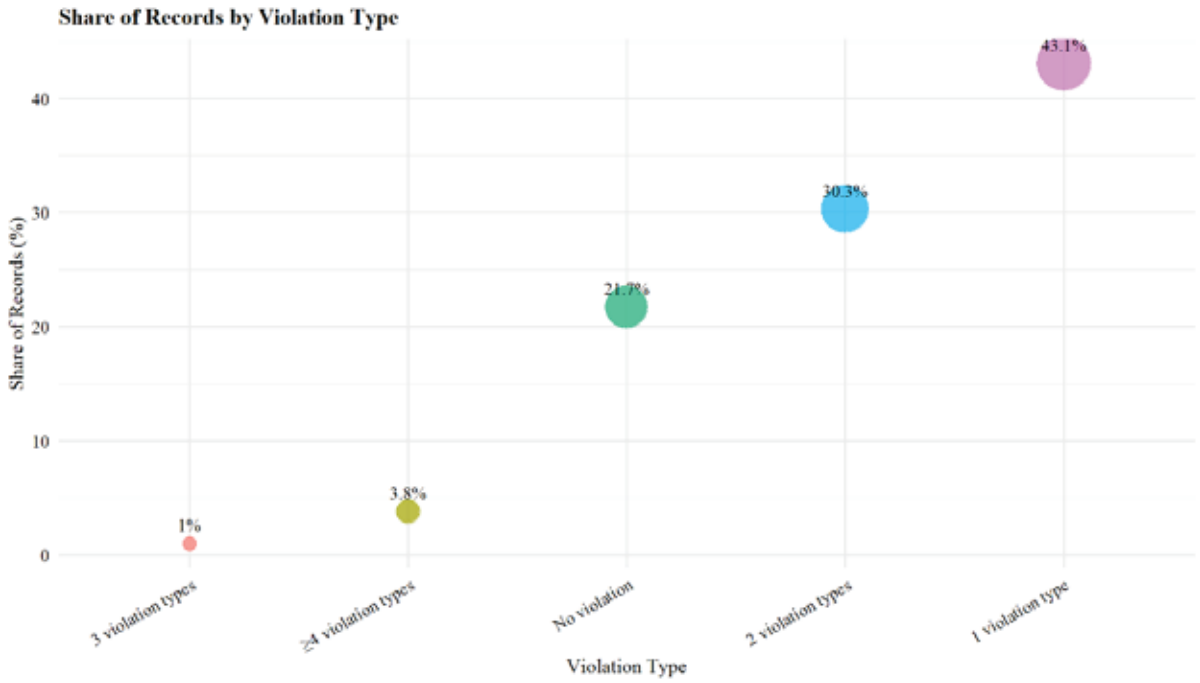

Fig. 2: Distribution of records by number of fisheries violation types detected

was performed at both the 99% and 95% confidence levels, enabling the identification of regions where the observed fishing intensity is improbable to happen by mere random chance, as illustrated in Fig. 3. The spatial analysis highlights distinct clustering patterns of high-intensity fishing violations, with hotspots concentrated in specific maritime regions that together depict the spatial dynamics of fishing pressure across Indonesia's waters. The most extensive continuous hotspot area lies in the Java Sea, Southern Natuna Sea, and Indian Ocean where dense fishing activity occurs near major landing ports in Java and adjacent coastal provinces.

The high concentration of fishing vessels in this area likely supports both lawful operations and opportunities for non-compliant practices, particularly in zones with rapid vessel turnover. In the eastern part, the southern Arafura Sea off Papua is known for its significant hotspots, which are located in one of the world's most valuable and productive fishing regions. Its vast size, remoteness, and limited monitoring capacity make it especially vulnerable to under-regulated fishing activity. Conversely, smaller and more localized clusters of hotspots can be found along the eastern coast of Sumatra, close to established fishing hubs in neighboring countries. These appear to be associated with artisanal and small-scale commercial operations, where spatial intensity is driven by proximity to coastal communities rather than industrial-scale fleets. Together, these regional patterns indicate that spatial clustering of fishing violations is shaped by an interplay of resource abundance, maritime connectivity, and enforcement accessibility, underscoring the need for geographically targeted monitoring and regulatory interventions. Conversely, the vast majority of grid cells are deemed "not significant," reflecting either a spread of activity or weak statistical clustering at the employed spatial resolution. The Gi* persistence map, generated at a 0.25° grid resolution over a 39-month period, reveals several maritime zones where hotspot status persisted for over 80% of the months, notably in the Java Sea, Natuna Sea, Sulawesi Sea, and Arafura Sea (Fig. 4). These patterns indicate sustained fishing pressure and recurrent violations, suggesting systemic non-compliance rather than isolated incidents. The spatial concentration of such high-persistence cells emphasizes the importance of sustained, targeted enforcement, as occasional patrols are not likely to interfere with entrenched illegal operations.

The persistence maps organized by violation type, covering a 39-month observation period as depicted in Fig. 5, showcase distinct spatial patterns and varying levels of temporal concentration for different categories of fisheries-related violations. While "All

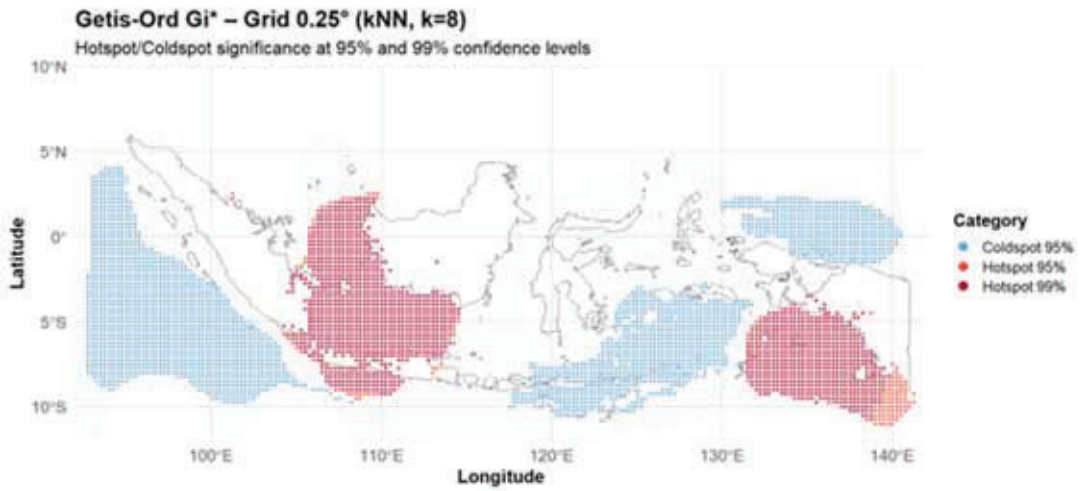

Fig. 3: Spatial distribution of fishing violation hotspots and coldspots in Indonesian waters identified using the Getis-Ord Gi* statistic (Grid resolution: 0.25°, kNN = 8). Hotspots (red) represent grid cells where violations are significantly clustered above the mean, while coldspots (blue) indicate significantly lower activity. The analysis covers the period 2010–2020 using Vessel Monitoring System (VMS) data, with significance thresholds at 95% and 99%, allowing consistent identification of persistent enforcement priority areas.

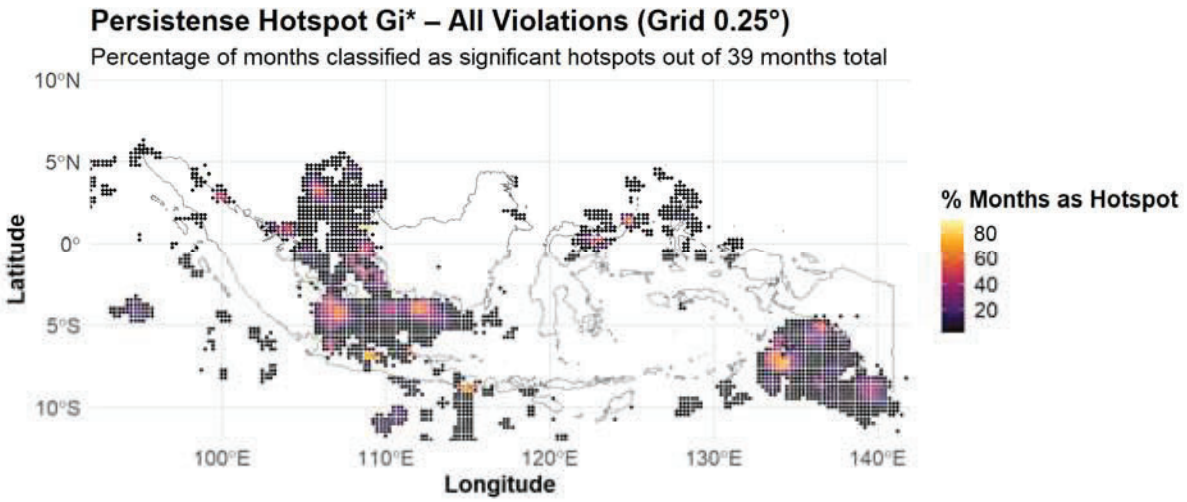

Fig. 4: Persistence of fishing violation hotspots in Indonesian waters based on the Getis-Ord Gi* statistic (Grid resolution: 0.25°). Colors show the percentage of months (out of 39, October 2021–July 2024) in which each cell was identified as a statistically significant hotspot. Warmer colors indicate higher persistence (i.e., cells repeatedly identified as hotspots), while cooler colors represent low persistence, helping highlight priority zones for long-term enforcement.

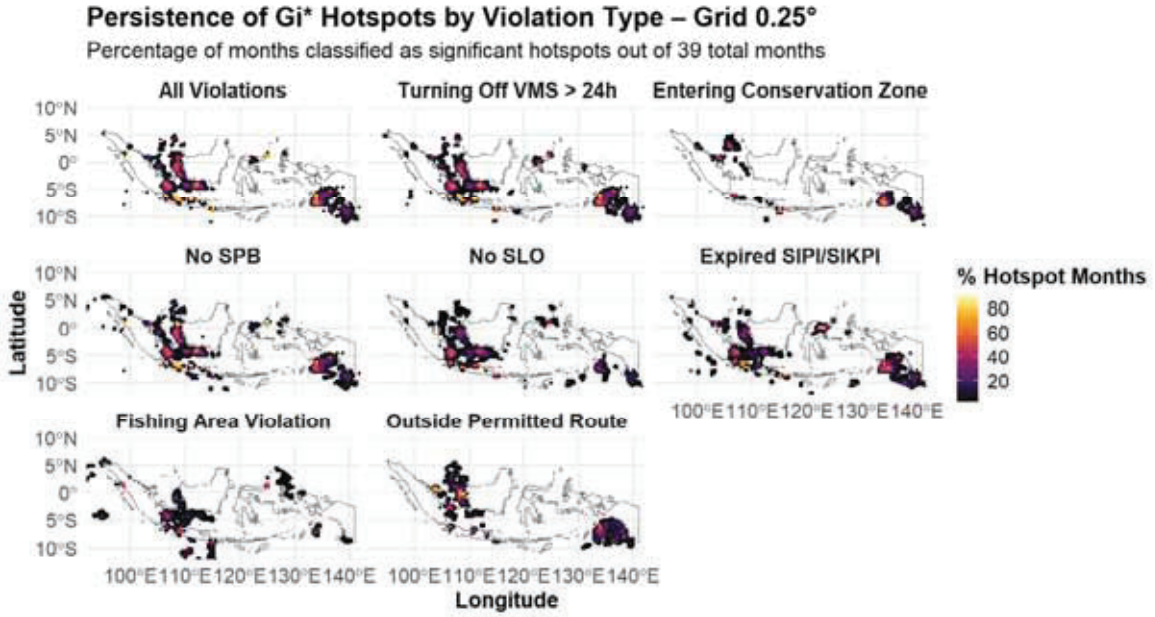

Fig. 5: Persistence of fishing violation hotspots in Indonesian waters by violation type, based on the Getis-Ord Gi* statistic (Grid resolution: 0.25°). Colors indicate the percentage of months (out of 39, October 2021–July 2024) in which each grid cell was classified as a statistically significant hotspot for a given violation type. Warmer colors represent higher persistence (i.e., cells where violations repeatedly occurred), allowing comparison of spatial patterns across major violation categories such as VMS disabling and incomplete SPB documentation.

Violations" exhibits broad clusters of high-persistence hotspots in the Central and Eastern Java Sea, southern Makassar Strait, and Arafura Sea, individual violation types show more localized and differentiated patterns. For example, "Turning Off VMS > 24h" and "No SPB" share extensive persistence in the Java Sea and Makassar Strait, whereas "Entering Conservation Zone" is more prominent in specific protected areas such as the Arafura region. "Incomplete or No SLO" and "Expired SIPI/SIKPI" hotspots concentrate in eastern Indonesia, particularly around Papua and Maluku waters. The term "Fishing Area Violation" is somewhat restricted in scope, yet it demonstrates a consistent presence in critical areas. Additionally, the phrase "Outside Permitted Route" is particularly common in the Arafura Sea. These differences suggest that enforcement strategies should be spatially tailored to target the dominant violation type in each high-persistence area, maximizing patrol efficiency and regulatory impact.

While, VMS provides mandatory and consistent coverage for licensed industrial vessels, it does not capture the activities of small-scale fleets below the tonnage threshold, creating potential monitoring gaps. Furthermore, VMS has the potential to produce false positives (for instance, stationary vessels may be incorrectly identified as active) or may be intentionally disabled, leading to biases in underreporting. These limitations underscore the importance of hybrid approaches that combine VMS with AIS, satellite imagery, or community-based monitoring to improve reliability and ensure comprehensive coverage across different vessel classes. An additional constraint is the absence of validation using independent enforcement or observer datasets to ensure the correctness of detected hotspots. While VMS-derived persistence and economic intensity provide a strong proxy for risk prioritization, direct comparison with patrol records, court cases, or on board observer data would strengthen confidence in the results. Future studies ought to investigate this validation to fine-tune hotspot models and enhance their practical significance for enforcement strategies.

Violation-type specific patterns

Fig. 6 shows the top 10% highest-risk hotspots for marine and fisheries violations in Indonesia, mapped at a 0.25° grid and clustered by spatial proximity. Twenty-one clusters were identified, with the Java Sea (7 clusters; 31 grids), Natuna Sea (5 clusters; 25 grids), and Arafura Sea (6 clusters; 19 grids) accounting for over 85% of all hotspots. These zones signify enduring centers of non-compliance, propelled by dense vessel traffic, precious fish stocks, and challenges in law enforcement in remote maritime regions. Violation patterns vary geographically: Turning off VMS > 24h and Incomplete or No SPB dominate in the Java and Arafura Seas; Entering Conservation Zones concentrates in eastern Indonesia; licensing violations cluster in Maluku and Papua; while fishing area violation and outside permitted route occur in smaller, scattered clusters near boundaries.

The concentration of more than 92% of recorded cases in two violation types—disabling events and license/document (SPB) infractions—also warrants careful interpretation. While this dominance may reflect genuine prevalence, it is partly shaped by system-level factors. For instance, incomplete SPB violations are likely prevalent due to the SPB database not being fully integrated with the Command Center platform, which results in reporting gaps that are recorded as noncompliance. Meanwhile, VMS disabling for more than 24 hours could reflect intentional behavior, such as concealing fishing grounds, making it systematically detectable in VMS records compared to other violations. Recognizing these biases and operational drivers helps avoid over-interpreting certain categories while highlighting the need for complementary monitoring methods and improved database integration. Simultaneously, enforcement strategies inevitably overlap with the livelihoods of small-scale and subsistence fishers, many of whom might unintentionally breach regulations because of limited awareness of intricate rules or inadequate access to necessary documentation. To address these equity concerns, recent MMAF initiatives have emphasized socialization, training, and the gradual roll-out of compliance requirements, ensuring that penalties are proportionate and coupled with opportunities for corrective action. The Ministry's emphasis on restorative justice—favoring administrative sanctions and corrective measures for minor offenses by small-scale fishers—reflects a broader recognition that enforcement must be equitable as well as effective. This approach becomes even more important in the context of climate change, which is expected to shift marine species distributions and alter fishing

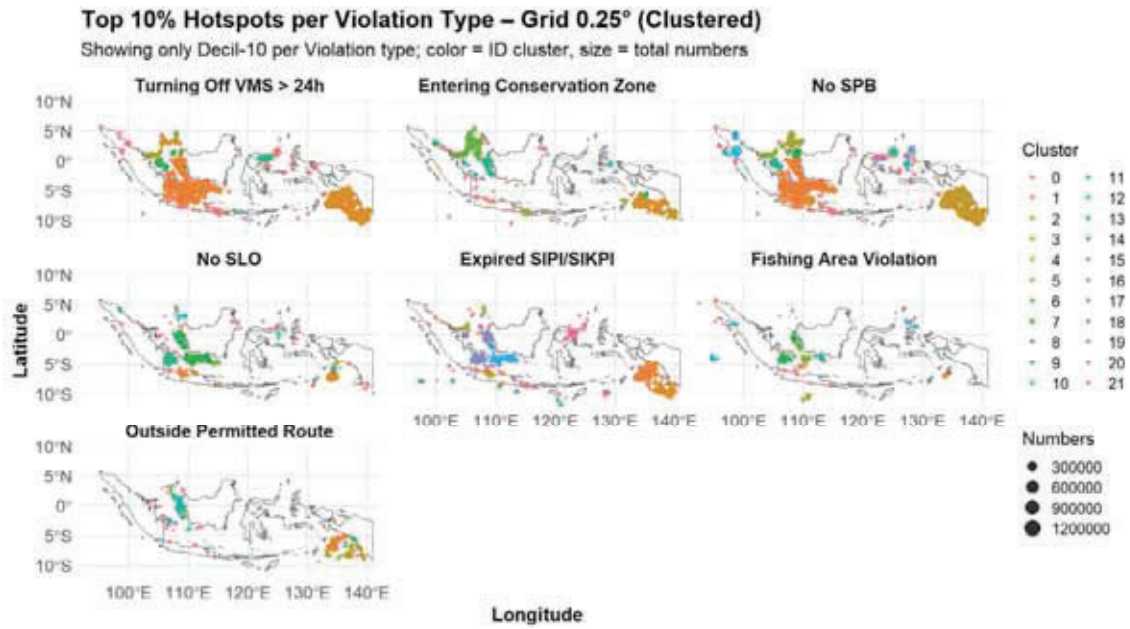

Fig. 6: Top 10% highest-risk fishing violation hotspots in Indonesian waters, disaggregated by violation type. Hotspots were identified using the Getis-Ord Gi* statistic on a 0.25° grid, with clustered analysis highlighting zones of concentrated activity. Colors distinguish different violation types (e.g., VMS disabling, incomplete SPB documentation), allowing visualization of which forms of non-compliance dominate the most persistent and severe hotspots. This highlights priority areas for targeted enforcement interventions.

hotspots, potentially pushing both industrial and small-scale fishers into new areas in search of resources. As valuable stocks shift to less observed or more isolated areas, the likelihood of IUU fishing could rise, particularly if regulatory frameworks and monitoring systems fail to evolve. Integrating climate projections into patrol planning, alongside vulnerability assessments of fishing communities, can help ensure that enforcement remains both targeted and socially responsive. This involves predicting future areas of stress, steering clear of unhelpful reactions, and facilitating collaborative solutions in developing hotspots (Rogers *et al.,* 2019; Beckensteiner *et al.,* 2023).

Economic intensity of hotspots

The greatest total catch values were recorded in the eastern and western regions of Indonesian territorial waters, with an average value 78 billion USD. Fig. 7 illustrates the spatial distribution of log-transformed economic intensity, showing substantial overlap with persistent Gi* hotspots.

The composite risk map integrates two essential elements of maritime surveillance: the frequency of suspected fishing activities in a given area and the economic significance of those operations. This results in a single score that ranges from 0, which indicates minimal risk, to 1, which signifies maximum risk. This study advances beyond prior research on IUU fishing in Indonesia, which has primarily emphasized either spatial clustering of violations (Ford *et al.,* 2018; Rahmadani *et al.,* 2020) or aggregate national economic loss estimates (Ali *et al.,* 2020; Khan *et al.,* 2024), but rarely their integration. By combining the Getis-Ord Gi* measure of spatial persistence with economic intensity derived from landed value, the strategy establishes a direct link between ecological risk and economic interests. This dual framework moves beyond descriptive hotspot mapping toward a decision-support tool that prioritizes enforcement not only where violations are persistent but also where economic consequences are most severe. The worldwide scarcity of similar applications implies that this integration serves as

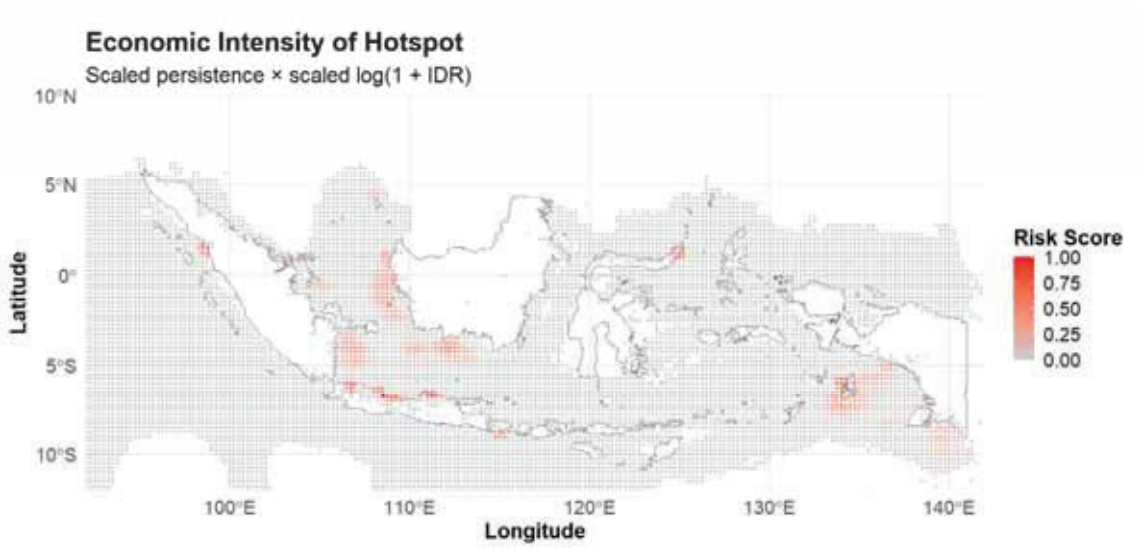

Fig. 7: Economic intensity of persistent fishing violation hotspots in Indonesian waters, emphasizing high-value zones in the Java Sea, Natuna Sea, and Arafura Sea. Economic intensity was calculated as the total landed catch value (USD) aggregated per 0.25° grid cell over the 39-month study period (October 2021–July 2024). Warmer colors indicate grid cells with higher cumulative economic value, overlapping with persistent violation hotspots, thus identifying priority areas where enforcement could yield the greatest economic returns.

a versatile approach to harmonizing enforcement resources with conservation and economic aims. The persistence measure reflects the frequency with which vessels are detected in specific grid cells, while the economic factor is derived from a scaled logarithmic transformation of the reported landed values emphasizing areas where illegal fishing could cause the greatest economic losses. The spatial analysis indicates a significantly uneven distribution of risk throughout Indonesia's territorial waters. Although most maritime zones display low composite risk scores, several concentrated high-risk clusters stand out with risk score > 0.5. The Java and Natuna Sea, which part of FMA 712 and 711 shows sustained vessel activity combined with high economic value, making it a critical focus for enforcement. The coastal regions of West and South Kalimantan, located within the Java and Natuna Sea, exhibit consistent trends that imply possible centers for illegal, unregulated, and unreported fishing, probably exploiting their nearness to significant landing ports. In the southern and northern waters of Papua, distinct hotspots appear near high-value fishing grounds, indicating heightened vulnerability due to remoteness and the difficulty of enforcement. Along the eastern coastline of Sumatra, moderate-to-high risk zones may be linked to intensive fishing pressure and the landing of lucrative species. An additional warning pertains to the evaluation of economic intensity, which in this analysis was calculated using the total value of the landed catch, not differentiating between species contributions. This approach provides a consistent aggregate measure but may be disproportionately influenced by a small number of high-value species such as tuna, skewing intensity patterns toward grids with even limited but high-value landings. While this does not diminish the utility of economic intensity as a prioritization tool, it highlights the need for species-disaggregated analyses in future work to ensure that enforcement priorities are not unduly driven by a narrow set of high-value species. Another limitation is that economic intensity estimates were not adjusted for market volatility or seasonal price differences. The study utilized aggregated annual landed values, offering a consistent long-term measure for economic prioritization, yet it may overlook short-term price fluctuations in commodities or the seasonal behaviors of high-value species. While this approach remains appropriate for identifying persistent enforcement priorities, incorporating price-adjusted or seasonally disaggregated values in future research would improve accuracy in reflecting real-time economic risks. Additionally, stronger regulations against IUU fishing could result in short-term changes in domestic

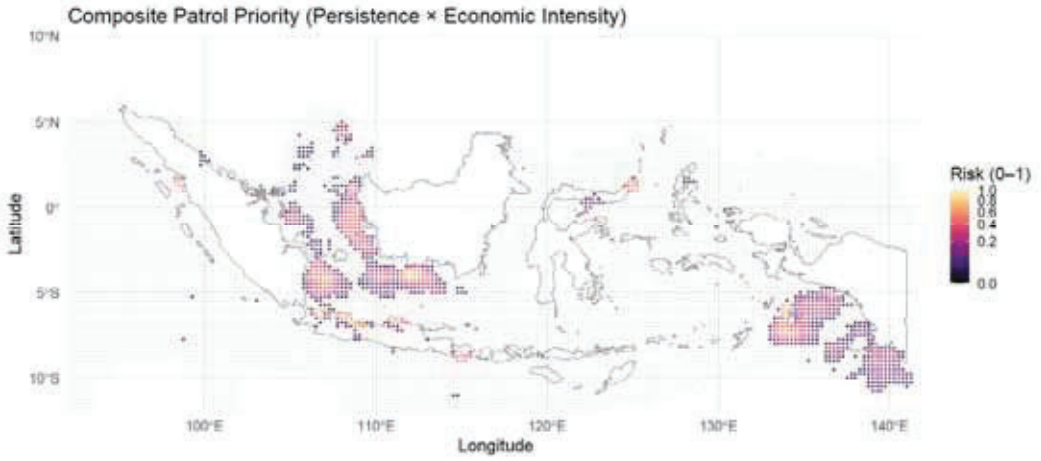

Fig. 8: Composite patrol priority zones in Indonesia's territorial and Exclusive Economic Zone (EEZ) waters, integrating hotspot persistence and economic intensity. The patrol priority score was computed by normalizing and combining the Getis-Ord Gi* hotspot persistence index (0.25° grid, October 2021–July 2024) with cumulative economic value of landed catch per grid cell. Warmer colors indicate higher-risk zones requiring enforcement prioritization, with the Java Sea, Natuna Sea, and Arafura Sea emerging as critical regions where targeted patrols could maximize deterrence and economic protection.

seafood market dynamics, affecting fish prices and the earnings of fishermen. By reducing unreported and illegal supply, stricter enforcement may initially raise market prices for certain high-demand species. While this benefits compliant fishers through higher revenues, it may also increase costs for domestic consumers, particularly in urban markets where seafood is a staple protein source. For small-scale or subsistence fishers, stricter enforcement could limit access if they lack proper documentation or licenses, potentially reducing their immediate incomes. To tackle these equity challenges, the Ministry has rolled out compensation and support initiatives, including streamlined licensing systems for small-scale vessels, the integration of compliance obligations into community-based training, and focused subsidies for fuel or gear improvements. These measures ensure that enforcement does not disproportionately burden vulnerable groups but instead strengthens long-term sustainability and legitimacy of domestic markets (Sahami *et al.,* 2024). A concrete example comes from Bitung, North Sulawesi, where stricter tuna enforcement in 2022 led to an initial decline in landings as illegal operators were curtailed. However, within a year, compliant fishers reported higher average revenues due to both improved stock conditions and price stabilization, as tuna prices in local landing ports rose by 12–15% (Khan *et. al.,* 2024). Arafura is expected to experience similar dynamics, as limiting illegal trawling can help preserve shrimp stocks and boost incomes for small-scale fishers over the medium term. Over time, enforcement is thus expected to stabilize fish stocks, support sustainable supply, and improve fisher livelihoods by reducing competition from illegal operators and opening greater opportunities in export markets.

Composite patrol priority

Integrating persistence and economic intensity produced the risk score map (Fig. 8). Top-decile risk cells (n = 910) accounted for 83.93% of the total estimated catch value from detected violations. These high-risk cells were heavily concentrated in the central and eastern Java Sea (particularly between the north coast of Java, western and southern Kalimantan), the Northern Sulawesi (Gorontalo and Bitung), and the Arafura Sea near Papua (especially along the coasts of Merauke and the Aru Islands). Smaller yet significant clusters were also observed in the Natuna Sea, located north of the Riau Islands, along the western coastline of Sumatra, which includes the waters off Aceh and West Sumatra, as well as in the northern Maluku area, particularly around Halmahera. The geographic concentration of these cells indicates that a relatively

small portion of Indonesia's maritime area accounts for a disproportionately large share of the economic risk from illegal fishing. This pattern underscores the potential efficiency gains of a targeted enforcement approach, where patrol and monitoring resources are directed toward a limited set of high-priority zones rather than dispersed uniformly. Such prioritization could significantly increase the likelihood of intercepting high-value illegal activity while reducing operational costs, particularly in remote regions where enforcement presence is currently limited. Furthermore, this analysis not only identifies spatial patterns but also introduces operational innovations that MMAF and other agencies could not accomplish with prior aggregate studies. The integration of persistence and economic intensity produces a composite patrol priority score, which shows that less than 10% of maritime grid cells (n = 910) account for over 80% of violation-related economic losses. This enables agencies to direct limited patrol assets toward these high-risk cells—concentrated in the Java Sea, Natuna Sea, and Arafura—rather than dispersing efforts uniformly across Indonesia's vast EEZ. Evidence-based targeting like this fosters innovations, including risk-focused patrol scheduling, specific licensing reforms for hotspots, and the phased introduction of surveillance technologies (e.g., drones, satellite monitoring) in the most crucial areas. By quantifying both the persistence and the economic stakes of violations, the framework gives MMAF a tool to move from broad deterrence toward precise, cost-efficient enforcement strategies. A concrete example can be drawn from the Arafura Sea, one of Indonesia's most persistent and high-risk violation zones. In fiscal year 2024, the Ministry of Marine Affairs and Fisheries allocated approximately USD 4.3 million to the Tual Surveillance Station, which is mandated to monitor violations in this region. According to national estimates, IUU fishing incurs losses of approximately USD 1.86 billion each year. The analysis indicates that the top-decile grid cells represent nearly 83.9% of this total, which amounts to around USD 1.56 billion. Consequently, the Arafura Sea is estimated to contribute between 20% and 30% of these significant losses, translating to USD 312 million to USD 468 million annually. If targeted enforcement efforts were able to reduce violations in this area by just 10–20%, the economic recovery would range between USD 31–94 million annually. When compared to the annual operational cost of the Tual Station, this represents a benefit-to-cost ratio of roughly 7 to 22 times. This finding highlights the efficiency of risk-based surveillance allocation and strongly supports the inclusion of cost–benefit models in future enforcement planning.

The examination of fisheries violation trends in Indonesia uncovers a concerning concentration of specific offenses, evident in both their high frequency and geographical distribution. The overwhelming dominance of two violation types—Turning Off VMS for More Than 24 Hours and Incomplete Notice of SPB—which together account for over 92% of valid national violations, is not simply a statistical anomaly; it is a symptom of deeper systemic weaknesses in vessel monitoring and documentation enforcement. The MMAF, as the key authority tasked with monitoring and enforcing compliance in Indonesia's expansive EEZ, confronts major obstacles in resolving these systemic issues. Prior studies confirm that such patterns often emerge where enforcement capacity is insufficient and legal frameworks are fragmented, allowing non-compliant behaviors to persist unchecked in expansive maritime jurisdictions such as Indonesia (Basri *et al.,* 2019). In a country with territorial waters covering more than 6 million km², these oversight gaps are intensified by the limitations of patrol resources and the logistical hurdles of surveilling extensive, isolated regions. This reality demands a technological leap. For MMAF, integrating advanced satellite-based systems such as Lembaga Penerbangan dan Antariksa Nasional (LAPAN) AIS-equipped satellites and Visible Infrared Imaging Radiometer Suite (VIIRS) night time light detection offers a critical opportunity to extend enforcement reach well beyond traditional patrol capabilities (Julzarika, 2017; Awak *et al.,* 2023). By merging these tools with the established VMS infrastructure, MMAF is capable of achieving near real-time detection of suspicious vessel conduct, facilitating the quick deployment of enforcement assets to high-risk regions and ensuring that remote waters no longer act as de facto safe havens for unlawful operators (Suharyo *et al.,* 2020). While the two dominant violations attract the bulk of MMAF's operational focus, other offenses—such as Entering Conservation Zones, Expired SLO, and Expired Fishing Licenses—pose equally serious threats when examined spatially. Despite their lower overall frequency, these violations

display a clear tendency to cluster in specific hotspot areas, indicating targeted exploitation of ecologically sensitive zones. Our analysis shows that several persistent violation hotspots overlap with ecologically sensitive areas such as coral reef ecosystems in Natuna, mangrove-fringe waters in Papua, and key spawning grounds in the Arafura Sea. This spatial convergence emphasizes the ecological trade-offs, since regions with significant economic intensity of violations also fulfill essential habitat functions necessary for sustainable fisheries productivity. For instance, the clustering of VMS-disabling events in the Arafura coincides with shrimp spawning areas, where unregulated extraction could accelerate stock depletion. Recognizing these overlaps justifies the inclusion of adaptive conservation zoning, whereby enforcement not only targets compliance but also strengthens ecosystem-based management. By aligning hotspot surveillance with conservation priorities, MMAF can integrate ecological resilience into enforcement strategies, ensuring that biodiversity protection and economic sustainability advance together. If unlawful fishing continues in pinpointed hotspots, the lasting ecological repercussions could be dire. Continuous overexploitation raises the risk of species collapse, especially for valuable demersal and pelagic stocks that sustain both export markets and local food security. Beyond fisheries, the degradation of spawning grounds, coral reefs, and mangrove habitats would diminish critical ecosystem services such as coastal protection, carbon sequestration, and biodiversity support, resulting in ecological losses that extend far beyond immediate catch declines. This alignment holds significant importance, especially since high-value fishing zones often draw illegal operations due to their abundant biodiversity, which justifies the increased risk of being detected (Yulia *et al.,* 2017). Evidence suggests that tuna species (skipjack, yellowfin, bigeye), Arafura shrimp, and various demersal reef fishes are among the groups most vulnerable to pressures in Indonesia's persistent violation hotspots. A study by Kasim *et al.,* 2024 on saddletail snapper (Lutjanus malabaricus) in the Arafura Sea indicates critical stock depletion, with a Spawning Potential Ratio (SPR) of just 17%—well below the 40% benchmark for a healthy population. Based on their MSY assessment, they recommend restricting annual catches to about 2,307 tons, underscoring the importance of aligning enforcement with science-based harvest limits to avert further decline. Similarly, demersal and reef fish populations in Natuna and surrounding shelves experience compounded stress from both overfishing and IUU practices, highlighting the need for co-managed spatial protections in reef and spawning habitats. The enforcement experience of MMAF illustrates worldwide trends, where marine protected areas are subject to continual violations despite existing legal protections, mainly because of the difficulties in overseeing resource-rich marine environments (Arias *et al.,* 2016; Quimbayo *et al.,* 2022). In such contexts, spatially targeted enforcement—rather than uniform, nationwide operations—would enable MMAF to concentrate patrol resources where they deliver the greatest ecological and economic returns. The rarest offenses—Fishing Area Violation and Fishing Outside the Permitted Route—may seem negligible in number, yet their spatial clustering tells a different story. These violations often occur along strategic maritime corridors, especially near international boundaries where MMAF must navigate both jurisdictional disputes and limited surveillance coordination. These locations are especially susceptible because the challenges of enforcement are intensified by complex border arrangements and minimal patrol visibility (Febriyanto and Setiaji, 2022). Similar conditions in other jurisdictions have shown that undelimited boundaries and overlapping maritime claims create persistent openings for illegal fishing (Afriansyah *et al.,* 2022; Song, 2021). In these situations, MMAF's efforts would benefit from bilateral and regional enforcement agreements supported by shared satellite surveillance platforms to close these jurisdictional and operational gaps. Examining the records in detail emphasizes the multifaceted challenge that MMAF confronts. While the bulk of violation records consist of one or two offenses, a significant 4.8% of cases involve three or more violations. These multi-offense incidents reflect deliberate, high-reward non-compliance strategies, exploiting the limits of MMAF's enforcement coverage. Behavioural research on fisheries violations suggests such patterns are influenced by the perceived probability of detection, economic incentives, and community norms (Susilowati, 2013). This implies that MMAF's technological investments must be matched by consistent on-the-water presence, strong deterrent penalties, and community

engagement programs to shift norms toward compliance. For successful operationalization of community-based monitoring, it is vital to enhance recognition with actionable support frameworks. Local fisher groups would require structured training in surveillance protocols and data reporting, clear legal authority to act as auxiliary enforcers or informants, and tangible incentives such as livelihood support, stipends, or preferential access to licenses. Incorporating these components into current initiatives—like KALAMO—would reduce enforcement expenses and improve legitimacy by harmonizing formal surveillance with traditional knowledge frameworks. For instance, the MMAF engages local fishers through the Smart-POKMASWAS program, which provides digital training and a geo-tagging application for rapid reporting of suspicious activities at sea. This approach transforms coastal communities into active surveillance partners, enhancing early detection and rapid response to IUU fishing violations. For example, community reports in the Natuna waters enabled MMAF to seize two Vietnamese vessels using prohibited trawl nets, demonstrating the effectiveness of community-based monitoring. Tackling these governance deficiencies is equally important as improving monitoring capabilities, necessitating cohesive legal frameworks, unified command structures, and established inter-agency coordination protocols to guarantee that focused enforcement in recognized hotspots produces lasting compliance results. Addressing these violation patterns requires a layered enforcement model. For MMAF, strengthening vessel monitoring and licensing systems is essential, but equally important is the adoption of spatial prioritization to ensure high-impact hotspots receive concentrated patrol attention. Initiatives focused on community monitoring can provide essential support, helping MMAF to broaden its surveillance reach in remote locations where continuous state-led patrols would incur prohibitively costly (Susilowati, 2013). Furthermore, harmonizing MMAF's national enforcement framework with Indonesia's international commitments, while clarifying legal provisions to avoid jurisdictional conflicts, will improve operational efficiency (Hehanussa *et al.,* 2014). The Gi* spatial analysis offers MMAF an evidence-based tool for prioritizing its enforcement activities. Persistent clusters of high-intensity violations in the Java Sea, Southern Natuna Sea, and Indian Ocean highlight areas where proximity to major landing ports and heavy vessel traffic create both economic opportunity and regulatory vulnerability. These findings align with prior research showing that high-traffic corridors are prone to entrenched illegal activity, as rapid vessel turnover undermines inspection capacity (Basri *et al.,* 2019). Another point of concern is the continuous presence of hotspots in remote, ecologically abundant waters such as the southern Arafura Sea—locations where MMAF's operational scope is heavily restricted. The combination of high resource abundance and low monitoring capacity makes these areas particularly vulnerable to chronic IUU fishing (Febriyanto and Setiaji, 2022). The Arafura exemplifies the challenge MMAF faces: vast, remote, economically valuable, and difficult to patrol at sufficient frequency to deter industrial-scale offenders (Yulia *et al.,* 2017). Not all hotspots are driven by industrial-scale activity. Smaller clusters along the eastern coast of Sumatra are likely indicative of artisanal and small-scale commercial fishing, with violations often resulting from economic necessity rather than intentional abuse of regulatory gaps. In such contexts, MMAF's enforcement approach must be sensitive to socio-economic realities, blending punitive measures with participatory co-management to sustain livelihoods while ensuring compliance (Susilowati, 2013). The persistence of many high-significance zones—remaining hotspots for over 80% of the 39-month observation period—confirms systemic, rather than opportunistic, non-compliance. As compliance research makes clear, such entrenched violations will not be disrupted by sporadic patrols; they require MMAF to maintain continuous, visible enforcement backed by a high likelihood of detection and meaningful sanctions (Viswanathan *et al.,* 1997). Persistence maps that are specific to violations give MMAF an essential operational advantage, uncovering not only the sites of violations but also the types that are most common in each hotspot. Persistent "Turning Off VMS" and "No SPB" clusters in the Java Sea, Arafura and Natuna Sea indicate monitoring evasion tactics best countered by enhanced real-time tracking and stricter port-based clearance checks. Conservation zone violations in the Arafura Sea point to the need for dedicated marine protected area patrol units, potentially co-managed

with local stakeholders (Yulia *et al.,* 2017). Ultimately, combining persistence analysis with economic valuation provides MMAF with a robust, data-driven foundation for focused enforcement. The Java Sea, Natuna Sea, and Arafura Sea together host more than 85% of identified high-risk hotspots, and their combined estimated landed value of USD 78 billion underscores the stakes involved (Febriyanto and Setiaji, 2022). The composite risk mapping strategy empowers MMAF to assign resources based on both the occurrence of violations and the potential economic and ecological impacts associated with each region. While the findings indicate that concentrating enforcement in a relatively small number of persistent and high-value zones could yield significant efficiency gains, the study did not perform a full scenario analysis of alternative resource allocation strategies. Such an analysis—comparing, for example, the effectiveness of evenly distributed patrols versus hotspot-focused deployments—would further substantiate the operational benefits of prioritization. Future studies should involve scenario-based simulations to evaluate trade-offs, supplying stronger evidence for decision-makers on how specific enforcement can maximize resource efficiency. However, by focusing on these high-priority areas—while maintaining a minimal deterrent presence elsewhere—MMAF can maximize interception rates and operational efficiency, particularly in remote regions such as Papua and Maluku (Susilowati, 2013). When supported by advanced monitoring technologies, predictive analytics, and community partnerships, such a strategy positions MMAF to adapt dynamically to shifting fishing patterns, closing enforcement gaps, and safeguarding both Indonesia's marine biodiversity and its fisheries-based economy.

CONCLUSION

Indonesia's enforcement experience offers transferable lessons for other developing coastal nations with limited resources. Through the integration of spatial analytics, economic valuation, and community-based monitoring, MMAF has demonstrated that intelligence-driven and equity-focused enforcement can enhance effectiveness without depending exclusively on expensive technologies. This balanced approach provides a replicable governance framework that strengthens compliance, reduces IUU fishing, and advances sustainability in the global south. This study presents the first integrated analysis of spatial–temporal persistence and economic intensity of fisheries violations across Indonesia's vast maritime domain, offering a data-driven framework to prioritize enforcement efforts. Using over 77 million VMS records from 2021 to 2024, the research identifies persistent hotspots of illegal, unreported, and unregulated (IUU) fishing activity, revealing that a relatively small number of high-risk zones—particularly in the Java Sea, Natuna Sea, Makassar Strait, and Arafura Sea—account for the majority of persistent violations and associated economic losses. The prominence of two violations—Turning Off VMS and Incomplete SPB—emphasizes critical weaknesses in compliance oversight and the enforcement of documentation practices. Despite their lower frequency, other violations such as encroachment into conservation zones and expired licenses show concentrated spatial clustering, often overlapping with ecologically sensitive areas. Additionally, it is crucial that enforcement approaches consider both widespread infractions and those that are geographically concentrated, as these can severely undermine ecological health and economic viability. The use of Getis-Ord Gi* spatial analysis, combined with economic valuation of landed catch, enables the identification of violation-specific, high-persistence zones and the generation of a composite risk score. This approach empowers the Ministry to transition from a reactive, diffuse enforcement strategy to a proactive, intelligence-led model. By focusing limited patrol resources on a targeted subset of high-risk zones—comprising less than 10% of maritime grid cells but responsible for over 80% of violation-related economic value—MMAF can substantially enhance surveillance efficiency and deterrence effectiveness. Furthermore, the results endorse a multi-tiered enforcement framework that incorporates sophisticated monitoring technologies (such as satellite-based AIS and VIIRS systems), predictive spatial analytics, and community-driven surveillance networks. This is especially crucial in remote and logistically challenging regions like Papua, Maluku, and the Arafura Sea, where enforcement capacity is low and non-compliance is entrenched. Adjusting enforcement strategies to reflect local violation trends further guarantees that regulatory measures

are responsive to ecological and social contexts. In addition to enhancing enforcement operations, these insights offer valuable contributions to broader fisheries governance. The ability to spatially forecast high-risk areas enables policymakers to refine marine spatial planning, adjust licensing frameworks, and deploy targeted capacity-building programs for local authorities. By proactively managing areas of high economic and ecological value, MMAF can reduce conflict, improve regulatory compliance, and foster more inclusive marine resource management practices. In conclusion, this analysis enhances Indonesia's standing in the realm of regional and international fisheries diplomacy. As violations frequently arise close to maritime limits, the hotspot maps and composite risk framework serve as a groundwork for cooperative enforcement initiatives with adjacent nations. Regional surveillance agreements, supported by transparent data-sharing mechanisms and shared monitoring infrastructure, could significantly reduce transboundary IUU fishing risks. As a further operational recommendation, high-persistence zones such as the Java, Natuna, and Arafura Seas should be prioritized for intensified patrols—ideally conducted on a weekly to biweekly basis—while satellite monitoring with revisit intervals of 1–3 days would provide near-real-time detection of suspicious activity. These focused strategies guarantee that scarce resources are utilized in areas that provide the highest ecological and economic benefits. In addition to government-led enforcement, market-driven approaches like insurance, certification, and eco-labeling initiatives present significant supplementary incentives to encourage compliance and mitigate the risks associated with IUU fishing. For instance, access to vessel insurance could be conditioned on proof of regulatory compliance and clean violation records, directly tying financial security to lawful operations. Similarly, participation in eco-labeling or sustainability certification programs (e.g., MSC, Fair Trade) can unlock premium export markets, granting compliant fisher's higher prices and market stability while excluding violators from these benefits. These mechanisms allocate a portion of the compliance obligations to private-sector participants and international buyers, thereby enhancing accountability throughout the supply chain. Although implementation requires administrative infrastructure and careful auditing, the potential benefits—greater market access, risk mitigation, and reputational value—justify the inclusion of such schemes as integral components of Indonesia's long-term IUU reduction strategy. By adopting these recommendations, Indonesia can safeguard its marine resources while also setting a precedent for sustainable and equitable ocean governance.

AUTHOR CONTRIBUTION

S.D. Diantara conceived the study framework and prepared the initial manuscript draft. I. Meilano oversaw the project and provided critical review of the draft. H. Latief contributed through supervision and by conducting a literature review. S.W. Trenggono provided critical review of the draft. W.I. Sakti supplied essential data and assisted in the literature review process. K. Kasim was instrumental in the analysis, editing and interpretation of the data. N.F. Gusmawati supported the development of the conceptual framework and the literature review. All authors reviewed and gave final approval for the manuscript prior to publication.

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CONFLICT OF INTEREST

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

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Negative AI Statement

The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

>	Greater than
≥	Greater than or equal to
%	Percent
0.25°	0.25 degree
AIS	Automatic identification system
Bakamla	Badan Keamanan Laut
CCSBT	Commission for the Conservation of Southern Bluefin Tuna
CI	Confidential interval
DPI	Fishing ground (Daerah Penangkapan Ikan)
e.g.	For example
FMA	Fisheries management area
EEZ	Exclusive economic zone
FAO	Food and Agricultural Organization
GT	Gross tonnage
MMAF	Ministry of Marine Affairs and Fisheries of Indonesia
MSC	Marine Certification Council
IUU	Illegal, unreported, unregulated
IUUF	Illegal, unreported, unregulated fishing
IOTC	Indian Ocean Tuna Commitee
KALAMO	Kampung Nelayan Modern
kNN	K-Nearest Neighbors
Km^2	Square Kilometer
Km	Kilometer
LAPAN	Lembaga Antariksa dan Penerbangan National
n	Number of sample
No.	Number
POKMASWAS	Kelompok Masyarakat Pengawas
Polairud	Kepolisian Perairan dan Udara
PSMA	Port State Measures Agreement
RFMOs	Regional Fisheries Management Organizations
SAR	Synthetic Aperture Radar
SIKPI	Surat Izin Pengangkutan Ikan (Fish transporting permit)
SIPI	Surat Izin Penangkapan Ikan / Fishing Permit
SLO	Certificate of operational worthiness for fishing vessels
SPB	Sailing Permit Notice for Fishing Vessels
USD	United States Dollar
VIIRS	Visible Infrared Imaging Radiometer Suite
WCPFC	Western and Central Pacific Fisheries Commission

WPP-RI	Wilayah Pengelolaan Perikanan Republic Indonesia
WTO	World Trade Organization

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ORIGINAL RESEARCH PAPER

Satellite- based drought indicators for supporting sustainable water management

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ABSTRACT

BACKGROUND AND OBJECTIVES: Over the past decades, pressures have placed the basin's ecological and hydrological systems at serious risk. The Azraq , located in eastern Jordan, is an essential ecosystem reliant on groundwater, which is facing growing threats from extended periods of drought and excessive groundwater extraction. This study aims to provide a comprehensive evaluation of hydrological drought, and demonstrate the value of satellite-based indices as decision-support tools for sustainable water resource management.

METHODS: Multi-temporal Landsat satellite imagery from 1990 to 2024 was analyzed to assess spatial and temporal variability in surface moisture conditions. Two remote sensing-based indices, specifically the normalized difference moisture index and the normalized difference water index, were implemented during eight benchmark years. The indices were evaluated for their sensitivity to moisture stress, their effectiveness in identifying hydrological deficits, and their ability to pinpoint persistent drought hotspots related to groundwate.

FINDINGS: Both indices revealed a consistent decline in surface moisture, with a marked reduction after 2000 that coincided with major drought periods and rainfall anomalies. Normalized difference moisture index exhibited increased sensitivity to localized surface moisture stress, while also successfully capturing hydrological deficits on a basin-wide scale. Persistent drought hotspots were identified in zones of intensive groundwater abstraction, with the Azraq Oasis exhibiting continuous water scarcity despite its historically water-rich status. While the years 1990, 1995, and 2020 showed localized improvements, 2000 reflected extreme drought conditions and 2020 displayed the highest recovery in surface moisture. Normalized difference moisture index highlighted greater spatial variability in drought severity, whereas both indices consistently demonstrated escalating drought conditions across the basin.

CONCLUSION: The results confirm worsening drought trends in the Basin and highlight the importance of satellite-based indices in supporting adaptive water management and policy development. To strengthen resilience, urgent measures are needed, including integrated drought monitoring systems, stricter regulation of groundwater abstraction, and restoration of critical wetland areas. It is recommended to implement complementary strategies such as demand-side management, enforcing limits on water usage, promoting agricultural practices that use water efficiently, and performing regular hydrological assessments. Integrating satellite-based drought monitoring into water governance frameworks can provide robust, science-based guidance for protecting the Azraq Basin against the combined pressures of climate variability and human activity.

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INTRODUCTION

Drought is an increasingly prevalent threat in arid and semi-arid areas, posing significant risks to water supply, ecological balance, and long-term socio-economic stability. Climate variability and shifting weather patterns add increasing challenges to environmental sustainability and natural resource management, particularly in semi-arid regions where water scarcity is already severe. Grasping the trends in long-term rainfall and their effects is vital for creating effective adaptation and resilience strategies (Sandeep Kumar *et al.,* 2025). In the Middle East, notably in Jordan, the consequences of extended dry periods, climate variability, and escalating water needs has caused a serious water resource deficit. The Azraq Basin in eastern Jordan presents this challenge, as it combines fragile hydro-ecological conditions with high anthropogenic pressures. Historically, a distinctive wetland characterized the area; however, the basin has experienced considerable environmental decline as a result of unsustainable resource extraction and ongoing drought conditions. In regions with limited ground-based monitoring networks, remote sensing (RS) provides a practical tool for monitoring drought dynamics at broad spatial and temporal scales, together with a robust geographic information system (GIS) database, both facilitate the visualisation of spatial data, aiding in the communication of findings to stakeholders, policymakers, and the public. This facilitates well-informed decision-making and aids in the promotion of sustainable water management practices (Rather *et al*., 2022, Odeh and Mohammad, 2024). In particular, hydrological indices derived from satellite data, such as the normalized difference water index (NDWI) and the normalized difference moisture index (NDMI), offer powerful, and cost-effective tools to detect surface moisture variations. These indices hold significant value groundwater basins like Azraq, where the availability of water serves as a crucial indicator of both ecological and hydrological stress. While these indices are applied, comparative and long-term evaluations stay limited in arid settings. Consequently, pinpointing the key sensitive indicators specific to local conditions is vital for advancing drought early warning systems and promoting sustainable water management practices in regions facing water scarcity (Psychalas *et al*., 2023; McFeeters, 1996; Mohammad *et al*., 2024; Ji *et a*l., 2011). Droughts are commonly described as long periods of significantly below-average precipitation, usually accompanied by high temperatures, leading to critical water scarcity. Drought impact generally increases when the lack of precipitation is coupled with heat waves, enhancing the vegetation's evaporative stress (Su *et al.*, 2017). These circumstances have emerged as a genuine global issue, especially in areas that experience significant climate fluctuations and susceptibility. Droughts affect ecological balance and influence a wide range of environmental components, especially freshwater resources, groundwater recharge, and water-dependent socio-economic sectors. Therefore, precise assessment and ongoing observation of drought occurrences are crucial for facilitating data-informed decision-making, executing mitigation strategies, and ensuring efficient resource distribution (Padrón *et al.,* 2020; Takeshima *et al.,* 2020, Wehner *et al.,* 2018). However, with the continuous impacts of climate change and increasing population pressures, water scarcity is expected to be more harmful in the coming years. The increasing strain on water resources could greatly impact agricultural output, leading to serious consequences for both the economy and national food security (Ghazaryan *et al.,* 2020; Mohammad *et al*., 2018). Drought adversely affects agriculture, forestry, and ecosystems, contributing to land degradation, crop failure, livestock loss, and decreased productivity, eventually risking livelihoods, especially in rural areas. Developing countries often exhibit greater susceptibility to these effects because of their restricted ability to adapt. Over time, a long drought can permanently reduce land productivity. Moreover, climate change is exacerbating drought conditions by interfering rainfall patterns, elevating temperatures, and modifying land-ecology interactions. These changes underscore the critical necessity for enhanced drought risk management and mitigation strategies (Nair *et al.,* 2024). Traditionally, drought characterization has relied heavily on indices derived from historical precipitation and temperature records. These climate- focused indicators have proven to be useful instruments for comprehending the onset, length, and intensity of droughts. However, the development of satellite RS technologies has significantly enhanced drought monitoring by permitting constant, spatially detailed, and near-real-time observations. When merged with traditional meteorological data, satellite-based

indicators strengthen the capacity to detect and track drought impacts with more significant accuracy and spatial coverage (Dai, 2011; Eriyagama *et al.,* 2009; Mohammad *et al.,* 2018; Mohammad *et al.,* 2024). This study fills a crucial void by delivering a comprehensive, multi-decade analysis of hydrological drought patterns in the Azraq Basin, covering the period from 1990 to 2024. Using Landsat imagery and two major RS indices, NDMI and NDWI, this research evaluates long-term trends in surface moisture, identifies hydrologically stressed zones, and assesses the temporal sensitivity of each index to drought events. These indices, derived from shortwave infrared and near-infrared spectral bands, are particularly effective for identifying shifts in moisture levels within groundwater-influenced and semi-arid regions. The findings provide critical input for strengthening national drought early warning systems and for informing sustainable groundwater and wetland management in water-scarce regions. RS helps overcome many of the limitations associated with traditional field surveys, providing consistent, repeatable, and spatially extensive observations (Basalumi *et al.,* 2018). When combined with terrestrial data, it greatly improves the precision and efficiency of managing environmental resources, covering uses like forest monitoring and evaluation (Wulder and Franklin, 2003). In recent years, Sentinel imagery has become a cornerstone of environmental mapping efforts, owing to its high-resolution multispectral capabilities, wide spatial coverage, and free accessibility, which collectively make it particularly suitable for detecting land cover changes, monitoring vegetation, and assessing water resources (Ekaputri *et al.,* 2024). The objective of the current study is to assess the long-term hydrological drought in the Azraq Basin and to valuate the effectiveness of satellite-based indices as instruments for sustainable management of water resources. This is parallel to various objectives: 1) Assess spatial and temporal trends in surface moisture from 1990 to 2024 using Landsat imagery. 2) Apply and compare NDMI and NDWI for detecting drought patterns and hydrological deficits. 3) Identify persistent drought hotspots, especially in areas with intensive groundwater extraction. 4) Evaluate the indices' sensitivity in capturing drought severity at local and basin scales. And finaly, 5. Provide recommendations for adaptive water management and policy-making to enhance basin resilience. This study was carried at the University of Jordan and with the field work in Azraq basin, Jordan between 2022-2024.

MATERIALS AND METHODS

The study area

Jordan is considered one of the most water-scarce nations globally, grappling with a significant and persistent crisis. The current per capita water availability is approximately 70 cubic meters (m^3) annually, which is well below the global water poverty line. Projections suggest this figure will decline further to approximately 60 m^3 per person per year by 2040 (NWS, 2016–2025). Such scarcity presents significant threats to both the economy and the environment. This issue is intensified by inconsistent annual rainfall and swift demographic transformations resulting from the influx of refugees from neighbouring countries (MWI, 2021). In addition, the sector's challenges are compounded by persistent issues of water insufficiency and mismanagement (Hussein, 2018; Alazzam, *et al.,* 2024). The Azraq Basin, historically identified for its unique wetland ecosystems and biological diversity, was once sustained by a shallow groundwater table and periodic surface flooding. This ecosystem has suffered considerable degradation in recent decades, primarily due to unsustainable groundwater withdrawal driven by agricultural and urban demands, coupled with intensified drought conditions resulting from climate change. This overexploitation has resulted in the drying of major springs, contraction of wetland areas (which vanished later), declining surface and subsurface moisture levels, and a marked change toward desertification. Consequently, the basin has changed from a hydrologically resilient zone into one of the most ecologically vulnerable areas in Jordan (Mohammad, *et a.l,* 2023). The Azraq Basin covers an area of approximately 12,710 square kilometres (km^2), with the majority, about 94 percent (%), located in Jordan, while the remaining portions are situated in Syria (5%) and Saudi Arabia (1%) (Ministry of Water and Irrigation (MWI, 2017). The Azraq Oasis is located at the middle of the Azraq Basin and originally spanned a naturally flooded area. In 1977, it was protected under the Ramsar Convention as a Ramsar site, due to its ecological significance. Up until the mid-1990s, the oasis was recognized as an outstanding illustration of a desert

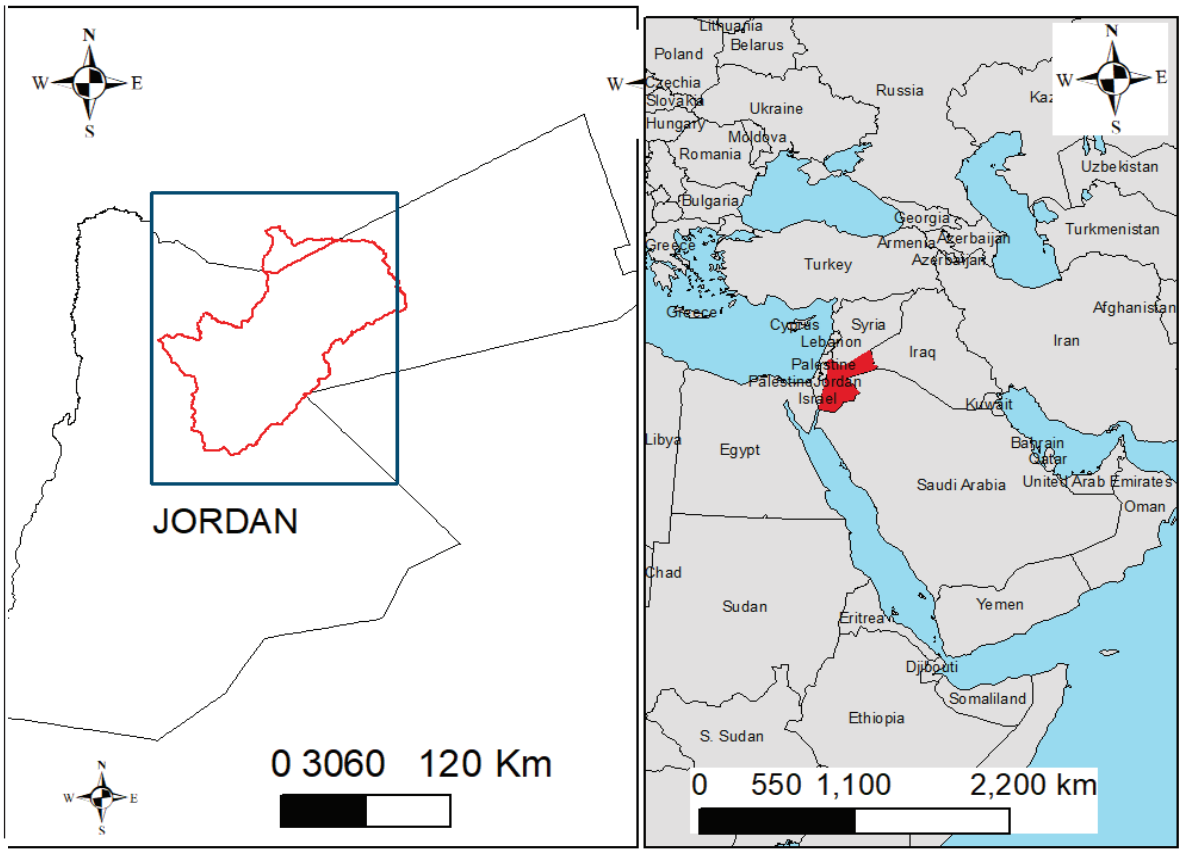

Fig. 1: Geographical location of the study area in Azraq basin in Jordan

wetland (Al-Eisawi, 2012). Despite this, the reserve has undergone considerable degradation in recent decades, with only about 15% of its original wetland area still existing today. Topographically, according to the digital elevation model (DEM), the basin spans a considerable elevation range. The highest point, approximately 1,576 meters above sea level (masl), is located in the Jebel El-Arab region of Syria.

Conversely, the lowest point is situated in the Azraq depression, which is positioned in the center of the basin, at around 500 meters above masl. Elevation gradually increases again toward the southern part of the basin, reaching approximately 900 masl (Fig. 1).

The basin is identified as a semi-arid to arid climatic region, distinguished by hot, dry summers and cool winters. Annual precipitation is highly irregular both spatially and temporally. Rainfall exceeds 325 millimetres per year (mm/y) in the northern highlands of Syria, dropping to around 150 mm/y in the western, and falling below 50 mm/y in the hyper-arid southern and eastern margins. The Azraq basin's average annual rainfall is approximately 122 mm (UNDP, 2014). Rainfall occurs predominantly during the winter season (November to March), often in the form of short-duration, high-intensity convective storms. This storm's rainfall pattern creates a risk of flash runoff, which limits the ability to recharge effectively and intensifies the pre-existing water scarcity problem (Abu-El-Sha'R and Rihani, 2006). Azraq includes one of the most significant groundwater basins in Jordan, supplying water to both local agricultural users and major urban areas, including the capital, Amman. The aquifer systems in Azraq have consistently been a major source of domestic water, particularly during dry years when surface water sources are inadequate. However, groundwater abstraction in Azraq often exceeds the safe yield, resulting in significant declines in groundwater levels and quality. However, the Azraq basin is considered one of the most drought-prone basins in Jordan, due to

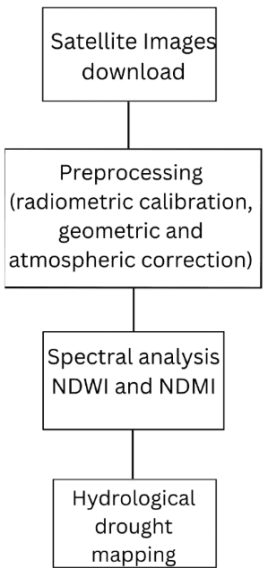

Fig. 2: Flowchart for the methodology of the study

its low and highly variable rainfall, high evaporation rates, and limited natural recharge. These factors, merged with over-abstraction of groundwater, make it a critical hotspot for hydrological drought. This study provides an extensive, long-term evaluation of hydrological drought conditions in the Azraq Basin, employing multi-temporal Landsat satellite imagery that spans 34 years (1990–2024). The analysis emphasizes two significant moisture-related remote sensing indices: NDWI and NDMI, which are used to examine variations both surface and subsurface moisture. The methodological framework integrates geospatial analysis, temporal trend evaluation, and cross-validation with historical drought records and rainfall anomalies to assess drought intensity and identify persistent hydrological stress zones. For the long-term analysis, eight benchmark years were selected: 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2024. The selection was conducted by two criteria: i) the availability of high-quality, cloud-free Landsat imagery, ensuring consistency across the study period, and ii) the alignment of these years with documented hydroclimatic extremes in Jordan. Specifically, 1990 and 1995 represent relatively wetter conditions, while 2000 corresponds to a well-documented drought year in the region. The years 2010 and 2015 were marked by consecutive dry phases that led to groundwater stress, further aggravated by the heightened demand due to the arrival of refugees in the country. In contrast, 2020 reflected a localized recovery linked to above-average rainfall. The most recent year, 2024, was included to provide an updated assessment of ongoing climate variability. This benchmark-year framework enables a structured comparison across decades, ensuring the inclusion of both drought and wet periods in the temporal analysis. To carry out this assessment, all Landsat images underwent standardized pre-processing procedures, which included geometric correction, radiometric calibration, and atmospheric correction, to guarantee data consistency and accuracy of the data across different years. Spectral analysis was then applied to derive NDWI and NDMI values for each benchmark year, facilitating the spatial and temporal quantification of water availability and moisture stress across the basin. The resulting indices were examined to identify patterns of hydrological drought and track their progression over time. Fig. 2 illustrates the overall data processing and analysis workflow used in this study.

Landsat imagery from the thematic mapper (TM), enhanced thematic mapper plus (ETM+), and operational land imager (OLI) sensors was obtained for eight benchmark years: 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2024 from the United States Geological Survey (USGS) website. These years were

meticulously selected based on several factors, including the accessibility of high-quality, cloud-free imagery during the periods that align with the peak of the growing season when vegetation and moisture patterns are at their most visible. This temporal distribution allows a representative assessment of hydrological changes and trends over more than three decades. The consistent spatial resolution 30 meters (m) and long-term continuity of the Landsat program make it particularly well-suited for monitoring environmental and land surface dynamics in arid and semi-arid regions like the Azraq Basin. The imagery underwent pre-processing to guarantee both radiometric and geometric corrections before calculating hydrological indices, facilitating comprehensive comparison across sensors and years. In this study, the potential underestimation of shallow, vegetation-covered waters was addressed by NDWI through careful image preprocessing and the complementary use of NDMI. NDMI facilitated the identification of vegetation moisture stress, enabling the differentiation of regions where vegetation might obscure shallow water signals. Additionally, high-resolution Landsat imagery was used to minimize the impact of vegetation on water detection. These methodological steps ensured that NDWI and NDMI together provided a more reliable representation of surface moisture and vegetation stress in the Azraq Basin.

Drought indices calculation

To evaluate multiple dimensions of drought, particularly agricultural and hydrological drought, two remote sensing-based indices were applied for each benchmark year. These indices were identified for their established efficacy in dry and semi-arid climates, in addition to their sensitivity to alterations in moisture levels.

1) NDWI

The NDWI was created to enhance and define open water features in satellite images, successfully differentiating water bodies from adjacent soil and vegetation. By using the difference between near-infrared (NIR) and green spectral bands, NDWI stops land and vegetation signals while strengthening the presence of surface water, making it a valuable tool for monitoring hydrological conditions, especially in drought-prone. NDWI is used to observe changes in the water content of leaves and surface moisture. It is susceptible to water and is proficient in detecting surface water bodies along with fluctuations in moisture within the vegetation canopy. Zero to +1 ranges indicate the existence of waterlogged area. In Landsat 8 imagery, band 3 instead of band 2 for Green and band 5 instead of band 4 for NIR have been used to match the wavelength variations between Landsat 8 and other Landsat series, using Eq. 1 (McFeeters, 1996):

$$NDWI = (Green-SWIR)/(Green+SWIR) \quad (1)$$

Where:

NIR: Near-infrared, and SWIR: Short-wave infrared bands.

In Landsat satellite imagery, the spectral bands used for calculating RS indices vary slightly between sensor generations. For the NIR band, Landsat 4 and 5 utilize Band 4, while in Landsat 8 and 9, NIR corresponds to Band 5. As for the SWIR band, it is represented by Band 5 in Landsat 4 and 5, and by Band 6 in Landsat 8 and 9. Interpreting these band assignments is key to maintaining uniformity in multi-temporal analyses, particularly when assessing indices like NDMI across various Landsat generations. NDWI reacts to both agricultural and hydrological drought conditions, helping to track wetland degradation in areas such as the Azraq Oasis.

2) NDMI

The NDMI is used to assess moisture levels in vegetation by combining NIR and SWIR spectral. It functions as a trustworthy signal of water stress in crops, facilitating for the prompt recognition of drought scenarios that may cause substantial yield reductions. NDMI is particularly effective in identifying water deficits before visible signs of crop stress appear, allowing for interventions. In agricultural settings, monitoring NDMI can support more efficient irrigation management, especially in regions where natural rainfall is insufficient to meet crop water requirements. Furthermore, in regions susceptible to wildfires, NDMI is utilized to evaluate the dryness and condition of vegetation, thus aiding in the monitoring and reduction of fire risks. NDMI is calculated by analyzing the reflectance of near-infrared and green light bands from satellite or aerial imagery. It is advantageous for recognizing water bodies, tracking variations in water availability, and

analyzing the condition of vegetation. NDMI is similar in structure to NDWI but is optimized for detecting changes in canopy water content. It is particularly valuable during drought periods as it reveals subtle moisture stress. NDMI is widely used in forestry and agriculture and proved helpful in this study to monitor seasonal and long-term moisture trends across the basin. NDMI is calculated using the NIR and SWIR reflectance, using Eq. 2 (Gao, 1996):

$$NDMI = (NIR-SWIR)/(NIR+SWIR) \quad (2)$$

Where:

NIR: Near-Infrared, and SWIR: Short-Wave Infrared bands.

For Sentinel-2, NDMI is derived from the near-infrared (Band 08) and short-wave infrared (Band 11) using the formula: NDMI = (B08 – B11) / (B08 + B11). In the case of Landsat missions, both Landsat 4-5 TM and Landsat 7 ETM+ using Eq. 3 (Goodarzi et al., 2019):

$$NDMI = (B04 – B05) / (B04 + B05) \quad (3)$$

Where: Band 4 represents NIR and Band 5 represents SWIR. For Landsat 8, the equation becomes NDMI = (B05 – B06) / (B05 + B06), corresponding to the updated band designations. The moderate resolution imaging spectroradiometer (MODIS) applies a similar formula, NDMI = (B02 – B06) / (B02 + B06), utilizing its specific NIR and SWIR bands. These variations reflect the adaptation of the NDMI across different RS platforms while maintaining its core purpose of assessing vegetation moisture content and water stress (Goodarzi et al., 2019). The NIR and SWIR bands were selected in the NDMI equation to minimize the effects of illumination differences and atmospheric interference. The SWIR band is especially responsive to the water content in vegetation and the internal structure of leaf mesophyll. In contrast, the NIR band captures high reflectance from the internal structure and dry matter of plant leaves. When these two bands are combined in NDMI, the resulting index delivers precise detection of vegetation moisture levels, reflecting a gradual decrease in moisture with fewer sudden value fluctuations.

RESULTS AND DISCUSSION

To evaluate the long-term drought patterns in the Azraq Basin, a collection of multi-temporal satellite images was acquired from the United States Geological Survey (USGS) EarthExplorer platform. A total of 16 Landsat scenes were selected across eight benchmark years—1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2024—grabbing seasonal and annual variations in vegetation and moisture conditions over 34 years. The selected images include data from Landsat 4-5 TM, Landsat 7 ETM+, Landsat 8 Operational Land Imager (OLI), and Landsat 9 OLI-2 sensors. These scenes represent path/row 173/037 and 173/038, which cover the full extent of the Azraq Basin. All scenes were picked during the spring months (March–May) to promote vigorous plant growth and limit cloud interference, ensuring consistent year-to-year comparisons. The images were preprocessed in GeoTIFF format and georeferenced to the WGS 1984 universal transverse mercator (UTM) Zone 37 North (N) coordinate system under the GIS software. All images have a 30m spatial resolution, which is suitable for basin-scale environmental and agricultural monitoring. All images underwent a detailed review of cloud cover, and only those scenes exhibiting minimal or no cloud presence (0–1.7%) were selected to guarantee the accuracy of spectral index calculations. The accuracy of drought detection in arid basins like the Azraq Basin is strongly influenced by the spatial and temporal resolution of the satellite sensors used. High-resolution sensors such as Landsat (30 m) and Sentinel-2 (10–20 m) provide detailed information on surface moisture and vegetation stress, enabling detection of localized drought hotspots, agricultural field impacts, and small water bodies. In contrast, sensors with coarser resolution such as MODIS (250–500 m) are better suited for detecting drought trends at the regional or basin level, thanks to their daily revisit frequency that enables near real-time observation of temporal changes. For operational drought monitoring in Jordan, combining these sensors can provide a synergistic approach: MODIS enables frequent detection of emerging drought events, while Landsat or Sentinel-2 supplies spatial detail necessary for targeted water management and agricultural planning. Integrating NDWI and NDMI indices across these sensors enhances both temporal sensitivity and spatial accuracy, supporting informed decisions on groundwater regulation, crop management, and drought mitigation strategies.

These datasets formed the basis for calculating five RS indices (NDWI and NDMI), enabling spatial and temporal analysis of drought-related vegetation and moisture stress throughout the study period. The spatial and temporal analysis of five RS, based drought indices, NDWI, and NDMI calculated across eight benchmark years from 1990 to 2024. Using Landsat imagery, the indices were generated to analyze changes in surface moisture and the general severity of drought within the Azraq Basin. NDMI utilizes the NIR and SWIR bands, making it particularly sensitive to vegetation water content and useful for assessing plant water stress. In contrast, NDWI, introduced by McFeeters in 1996, is calculated using the Green and NIR bands, which enhances the detection of open surface water bodies. While NDWI is effective for monitoring water bodies and detecting slight changes in surface moisture, it has limitations, particularly in urban areas, where built structures may be mistakenly classified as water due to similar reflectance characteristics, leading to potential overestimation. By leveraging the spectral properties of visible green and NIR wavelengths, the NDWI effectively identifies water bodies in contrast to other land features. The visible green wavelengths enhance the typical reflectance of water surfaces, while the NIR wavelengths, which are strongly reflected by vegetation and soil, show low reflectance over water. This contrast enables the NDWI to separate water from land. As a consequence, water features often generate positive NDWI values, while vegetation and soil regions result in zero or negative values, facilitating precise identification and tracking of surface water distribution. The maps produced depending on the NDWI for the Azraq Basin indicate a continuous pattern of hydrological drought across most of the study years from 1990 to 2024 (Fig. 3). The basin predominantly displayed low NDWI values, ranging from -0.3 to 0, which indicates considerable surface moisture stress and a scarcity of surface water. This pattern was particularly noticeable in regions related to substantial water storage. Only in the years 1990, 1995, and 2020 did the oasis area reflect relatively humid conditions, likely due to average rainfall during those winters or higher water recharge events. In contrast, the other years showed dry conditions even in these zones, indicating a progressive decline in water availability.

The observed trend can be explained by the growing dryness of summer conditions, the occurrence of shorter and more unpredictable rainy seasons, and a transformation in rainfall patterns, both in intensity and distribution. The decline in rainfall and infiltration has negatively impacted surface water recharge, leading to drying wetlands and shrinking reservoirs. These hydrological shifts have serious ecological and socio-economic consequences, including the degradation of wetland habitats, reduced agricultural productivity, and increased pressure on already-stressed groundwater resources. The NDWI outcomes therefore present strong evidence of an escalating hydrological drought in the basin, emphasizing the importance of implementing sustainable water management practices. The Azraq Oasis is a shallow, vegetated, and turbid natural wetland, so low basin-wide NDWI values do not contradict the presence of year-round surface water: the oasis occupies a small fraction of the basin, and its spectral signature is highly influenced by emergent vegetation (shrubs, bamboo), submerged plants, and suspended sediments. Landsat's 30 m pixels commonly become mixed at the oasis margin (water + vegetation + soil), producing lower NDWI values than those of open, deep water. Turbidity and aquatic vegetation reduce the contrast in the green and NIR bands that NDWI relies on, while surrounding bright soils and salt crusts further dilute the signal at the basin scale. It should be highlighted that analyzing NDWI in varied landscapes, such as the Azraq Basin, encounters frequent challenges, since overall values might remain low despite the presence of a natural oasis exists year-round. This is mainly due to scale and averaging effects, since Landsat's 30 m resolution produces pixel-based values that, when aggregated at the basin scale, are dominated by extensive drylands, making the dam's contribution statistically negligible. Additionally, spectral mixing occurs when individual pixels capture both water and adjacent land, thereby reducing NDWI values. Pure water pixels show positive values (>0.2), while mixed pixels trend closer to zero. The impact of adjacent land cover adds complexity to detection, as the high reflectance from bare soil, stressed vegetation, or saline surfaces—often found in arid environments—diminishes contrast and can distort the water signal, particularly when evaporation results in salt crusts or moist soils. NDWI is also more sensitive to large, open water bodies than to small reservoirs, shallow water covered by vegetation, or turbid water typical

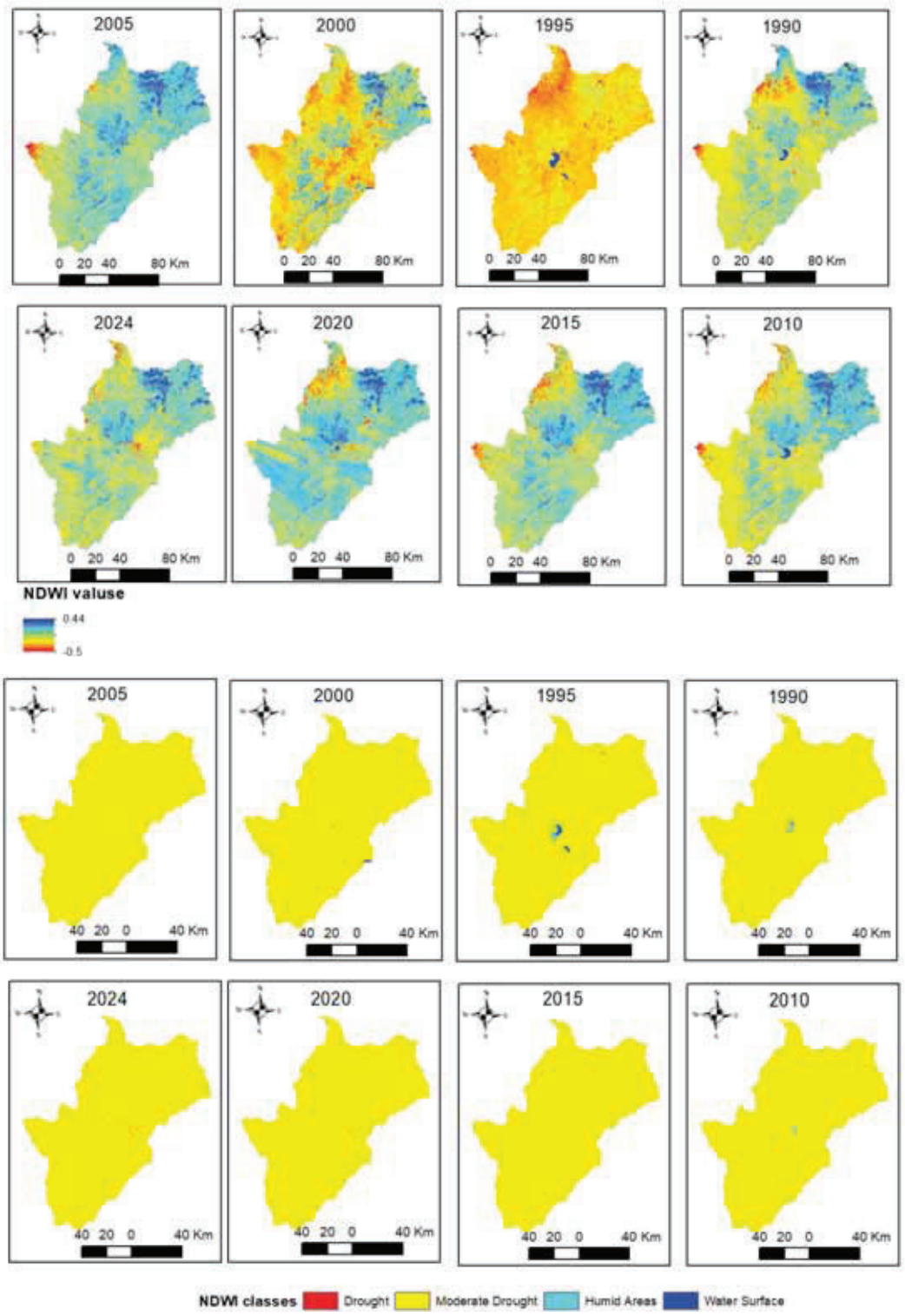

Fig. 3: NDWI values and classes maps for the targeted basin over the study period

of arid-region dams. Further, the oiases area remains relatively small and hydrologically stable, it does not significantly affect temporal NDWI trends, leaving basin-wide signals dominated by persistent drought conditions rather than localized water presence. NDMI has values ranging from -1 to +1, making it straightforward to interpret. Negative values approaching -1 typically indicate severe water stress or dry vegetation conditions, whereas values closer to +1 suggest excessive moisture or potential waterlogging. Medium values indicate a spectrum of vegetation water content, assisting in the identification of various agronomic conditions. This continuous scale enables effective monitoring of crop health, irrigation efficiency, and drought severity across landscapes. In other words, a reduction in NDMI indicates water stress, while high NDMI values reflect the presence of water bodies or moisture-rich areas. Unlike NDWI, NDMI offers a more detailed classification system with a broader number of classes, which allows for higher representation of moisture variability across the landscape. Consequently, variations emerge between the NDWI and NDMI results, particularly regarding the spatial distribution of drought intensity, as illustrated in Fig. 4.

Throughout all study years, NDMI showed a presence of both drought zones and moderately wet areas within the Basin. Nonetheless, the year 2000 is notable as the most significant year, exhibiting extensive regions categorized under the severe drought classification. This can be directed by a combination of low rainfall and long dry periods during that year, which drastically reduced soil moisture. Conversely, the year 2020 exhibited the greatest average wet areas throughout the study period, likely attributed to a comparatively wetter winter season and possibly enhanced surface water conditions. These fluctuations stress the impact of both seasonal rainfall characteristics and human activities, such as land use changes and irrigation practices, on surface moisture conditions in arid environments like Azraq. The analysis comparing NDWI and NDMI findings reveals a complementary relationship between the availability of surface water and the moisture stress experienced by vegetation and soil across the Azraq Basin. However, the two indices are derived from different spectral properties and represent distinct aspects of hydrological conditions—NDWI for surface water and NDMI for vegetation and soil moisture—they both reflect the wider impact of drought dynamics. Years indicated by low NDWI values, such as 2000, also showed widespread severe drought in the NDMI results, indicating that the decline in surface water was likely accompanied by decreased soil moisture and heightened vegetation stress. Conversely, in 2020, both indices demonstrated a notable improvement in conditions, highlighting the impact of a wet winter season that facilitated improved surface water storage and vegetation recovery. However, the spatial distribution of NDMI sometimes showed moderately moist zones in areas where NDWI remained low, which can be attributed to localized factors such as irrigation or land use changes that sustain vegetation moisture independently of surface water presence. This relationship underscores the importance of using both indices together to capture the full spectrum of hydrological drought effects, especially in complex arid environments like Azraq where human interventions and climatic variability both shape water availability. Collectively, the comparison reveals that NDWI is an effective indicator of widespread surface water scarcity. At the same time, NDMI delivers additional insight into vegetation and soil moisture dynamics, offering a more subtle picture of hydrological stress. At the oasis level, NDWI underestimates open water due to vegetation cover and turbidity, whereas NDMI captures the surrounding wetland's ecological condition more effectively. For basin-wide drought evaluations, the NDWI emphasizes consistent water shortages, whereas the NDMI enhances this by identifying spatial variability and regions where moisture stress has been alleviated. These results highlight the value of combining both indices in integrated monitoring systems: NDWI as a direct indicator of surface water availability and NDMI as a representative for ecosystem moisture resilience under climatic and anthropogenic pressures. The evaluation of NDWI and NDMI value throughout the study period demonstrated distinct temporal fluctuations, representing phases of moisture stress and hydrological deficiencies. For instance, the NDWI ranged from –0.36 to 0.21 in 1990, with an average of –0.075, while NDMI values varied between –0.28 and 0.48, averaging 0.1, indicating moderate water stress in certain years. Similar trends were observed across subsequent years, highlighting persistent drought hotspots that align with patterns of groundwater

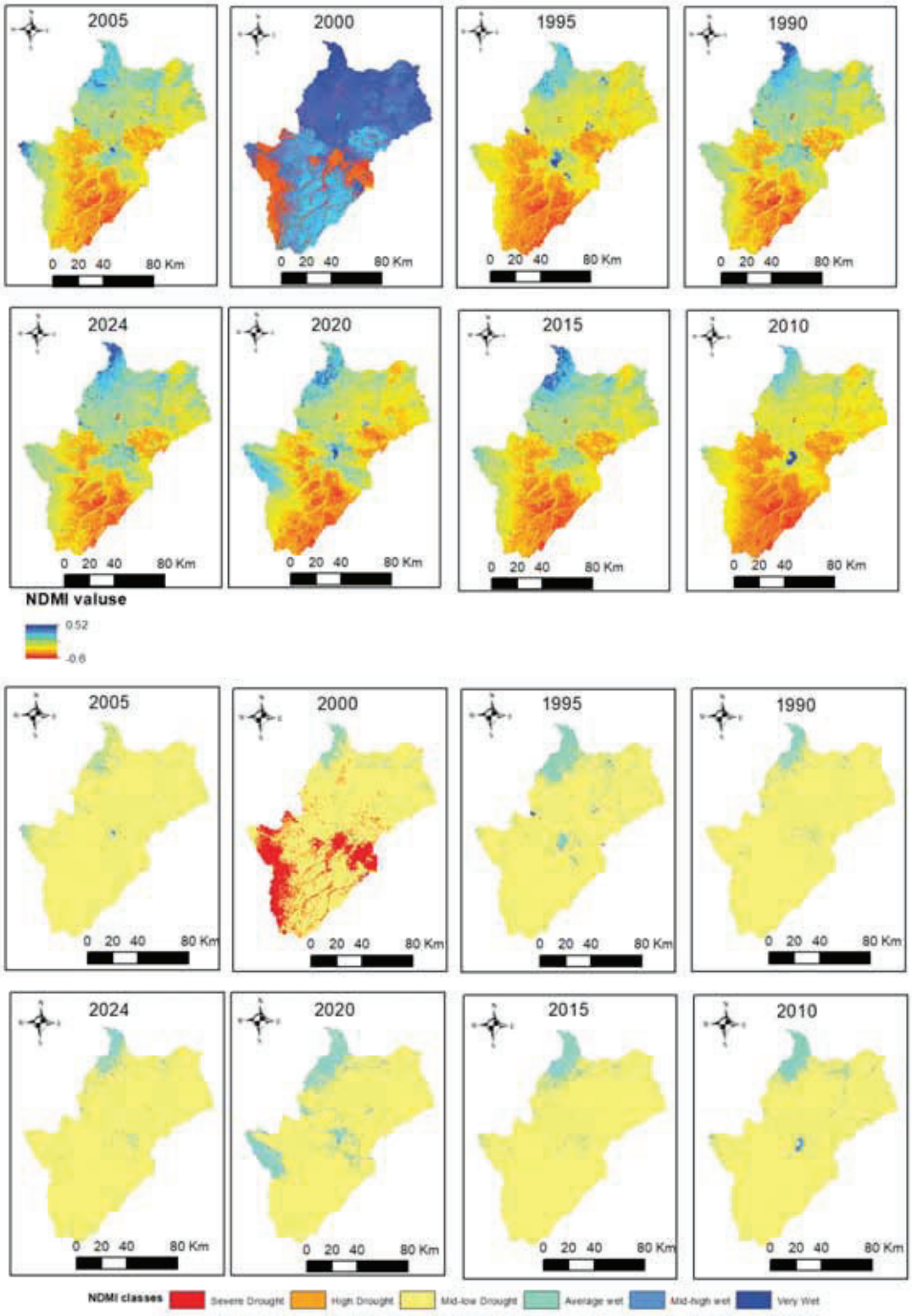

Fig. 4: NDMI values and Classes maps for the targeted basin over the study period

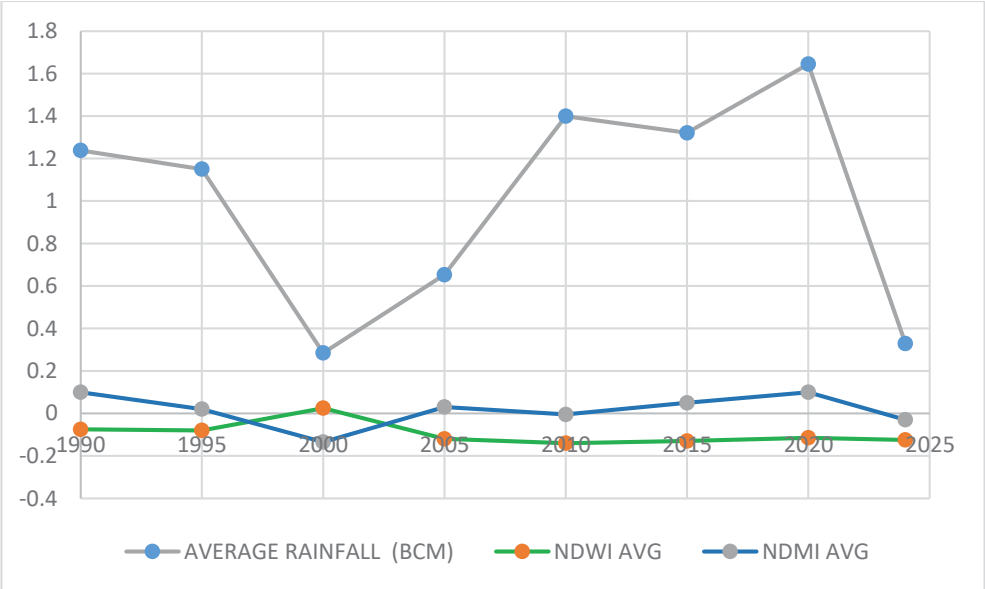

Fig. 5: Averages of: rainfall in Billion Cubic Meters (BCM), NDWI, and NDMI records over the study period

abstraction (Fig. 5).

The records reveal hydroclimatic variability over the past three decades. In 1990 (1238 MCM) and 1995 (1150.3 MCM), rainfall was relatively high, consistent with moderate NDWI and NDMI values indicating favourable water and vegetation conditions. In 2000, there was a significant drop in rainfall, which fell sharply to just 285 MCM, marking it as one of the driest years recorded. Both indices reflected this event through strongly negative anomalies, highlighting severe hydrological stress. By 2005 (653.2 MCM), rainfall partially recovered, which was also captured in the indices as a modest improvement in surface moisture and vegetation conditions. Rainfall levels increased again in 2010 (1,399.5 MCM) and remained high in 2015 (1,321.2 MCM), compared with more positive NDMI signals that captured vegetation recovery, while NDWI showed improvements in surface water-related conditions. The peak rainfall in the series occurred in 2020, totaling 1644.9 MCM, which was a notably wet year. During this time, both indices showed significant recovery, indicating an average year. However, this was followed by another extreme drought in 2024, during which rainfall plummeted to 329 MCM, as reflected by strong negative anomalies in both indices. To validate the remote sensing–derived drought indices, rainfall data from the MWI for the Azraq Basin were analysed for the benchmark years (1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2024). The recorded rainfall amounts serve as an essential ground-based benchmark for evaluating the trends of NDWI and NDMI (Fig. 5). In order to strengthen the validation of these satellite-derived indices, they were assessed against the rainfall data obtained from the MWI stations. The observed precipitation trends closely matched the fluctuations captured by NDWI and NDMI, reinforcing the reliability of these remote sensing indices as indicators of hydrological stress. Instances of subpar rainfall coincided with diminished NDWI and NDMI values, reinforcing the importance of integrating satellite imagery with ground-based observations for comprehensive drought monitoring and water resource management. A review of NDWI and NDMI data spanning from 1990 to 2024 indicates a noticeable decrease in surface moisture levels and ongoing low water content in vegetation, pointing to escalating drought conditions in the examined region. Annual mean NDWI ranged from –0.14 in 2010 to 0.025 in 2000, while NDMI means fluctuated between –0.135 in 2000 and 0.1 in 1990. Median values provide additional robustness, with NDWI declining from –0.125 in 1990 to –0.153 in 2024 and NDMI showing persistent low values in several years (Table 1). Mann-Kendall trend analysis confirms a statistically significant declining trend for both indices ($p < 0.05$), with Sen's slope indicating a gradual

Table. 1: Summary of annual NDWI and NDMI statistics (1990–2024)

Year	NDWI min	NDWI max	NDWI AVG	NDMI min	NDMI max	NDMI AVG	Median NDWI	Median NDMI
1990	–0.36	0.21	–0.075	–0.28	0.48	0.10	–0.125	-0.053
1995	–0.41	0.25	–0.080	–0.48	0.52	0.02	–0.137	-0.062
2000	–0.39	0.44	0.025	–0.60	0.33	–0.135	–0.131	-0.128
2005	–0.42	0.18	–0.120	–0.44	0.50	0.03	–0.118	-0.073
2010	–0.39	0.11	–0.140	–0.41	0.40	–0.005	–0.127	-0.055
2015	–0.45	0.19	–0.130	–0.30	0.40	0.05	–0.151	-0.053
2020	–0.48	0.25	–0.115	–0.26	0.36	0.05	–0.496	-0.04
2024	–0.50	0.25	–0.125	–0.28	0.22	–0.03	–0.153	-0.053

reduction in surface moisture over the study period.

Comparison with annual precipitation data from MWI stations shows that periods of below-average rainfall coincide with lower NDWI and NDMI values, validating the remote sensing indices as accurate indicators of hydrological stress. These findings carry significant consequences: a decrease in surface moisture may intensify groundwater stress, diminish agricultural output, and heighten the susceptibility of local ecosystems. The combined use of NDWI, NDMI, and rainfall data enables the identification of drought hotspots, supporting targeted water resource management and sustainable groundwater abstraction strategies. For operational drought monitoring in Jordan, NDWI is recommended as the primary indicator due to its consistent response to precipitation deficits and its ability to reflect broad hydrological stress. NDMI can function as a supplementary index for recognizing moisture stress related to vegetation, especially in farming zones. Together, these indices provide a robust framework to identify drought hotspots, guide water allocation, and support adaptive management strategies, offering practical tools for policymakers and water managers in water-scarce regions. The validation strengthens the trustworthiness of utilizing satellite indices as tools for decision support in integrated water management, necessitating the consideration of basin-scale dryness in relation to localized ecological indicators, including those observed in oiases. Analysis of NDWI and NDMI over the study period (1990–2024) reveals clear temporal variations reflecting hydrological conditions. NDWI annual averages ranged from –0.14 in 2010 to 0.025 in 2000, while NDMI averages fluctuated between –0.135 in 2000 and 0.1 in 1990. Including median values provides additional robustness: median NDWI declined from –0.125 in 1990 to –0.153 in 2024, and median NDMI values, although showing minor fluctuations, indicate persistent low moisture conditions in several years. Years with more negative median NDWI values, such as 2015 (–0.151) and 2024 (–0.153), correspond to periods of reduced rainfall, highlighting intensified hydrological stress in the study area.

CONCLUSION

The assessment of NDWI and NDMI across the Azraq Basin from 1990 to 2024 provides obvious evidence of drastic and spatially expanding hydrological drought. NDWI indicated ongoing surface water scarcity, with only short improvements in 1990, 1995, and 2020, which were correlated to average rainfall. NDMI supported this by capturing spatial variability in soil and vegetation moisture, with 2000 showing extreme drought and 2020 reflecting partial recovery. The indices collectively emphasize that changing rainfall patterns, diminished natural recharge, and excessive groundwater extraction are contributing to ecological deterioration and the decline of wetlands in this vulnerable basin. Statistical results support these patterns: the median NDWI dropped from –0.125 in 1990 to –0.153 in 2024, while the NDMI fluctuated but consistently indicated low moisture levels. The Mann-Kendall test proved significant negative trends for both indices, underscoring a worsening hydrological scenario. Notably, rainfall validation affirms the robustness of NDWI and NDMI as enduring drought indicators in Azraq, rendering them trustworthy tools for integrated monitoring. From a management perspective, these findings highlight the need for urgent action. NDWI and NDMI should be merged into drought early warning and decision-support systems to guide interventions such as regulating groundwater abstraction, restoring

wetlands, and adopting water-efficient agricultural practices. Their combined application of these indices provides complementary insights. NDWI indicates surface water shortages, while NDMI reflects vegetation stress, leading to a more comprehensive understanding drought dynamics. The integration of remote sensing indices with machine learning (ML) and multi-source datasets (precipitation, land use, soil data) could enhance predictive drought forecasting and proactive water allocation planning and support the process of decision support systems (DSS) . NDWI and NDMI can also be linked to economic loss assessments, identifying impacts on crop yields and grazing productivity, while guiding targeted interventions, such as groundwater recharge projects, in persistently dry zones. This study illustrates the importance of NDWI and NDMI as practical tools for assessing drought conditions in arid regions dependent on groundwater. Their systematic integration into policy and management frameworks provides a pathway to strengthen climate adaptation, protect ecosystems such as the Azraq Oasis, and promote sustainable water resource governance in Jordan.

AUTHOR CONTRIBUTIONS

A.H. Mohammad, the corresponding author, supervised the other authors in the analysis of NDWI and NDMI data, interpreted the results, prepared all maps and figures, and drafted the manuscript. M. Ghanem secured funding for the project and contributed to the interpretation of the results. A. La Hera-Portillo participated in the interpretation of the RS results and assisted in manuscript preparation. A. Alrowad contributed to manuscript preparation and provided oversight on wáter management and decision support system. K. Shatanawi participated in result interpretation and manuscript preparation.

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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.

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ABBREVIATIONS

%	Per cent
amsl	Meters above mean sea level
AI	Artificial intelligence
B	Band
BCM	Billion Cubic Meters
DEM	Digital elevation model
DSS	Decision support system
GIS	Geographic information system maintained by Esri
ETM+	Enhanced thematic mapper plus

km²	square kilometres
m	meters
ML	Machine learning
m³	cubic meters
mm	millimetres
mm/y	Millimetres per year
MODIS	Moderate resolution imaging spectroradiometer
MWI	Ministry of water and irrigation
N	North
NDMI	Normalized difference moisture index
NDWI	Normalized difference water index
NIR	Near-Infrared
OLI	Operational land imager
RS	Remote sensing
SWIR	Short-wave infrared bands
TM	Thematic Mapper
USGS	United States Geological Survey
UTM	Universal transverse mercator
WGS 1984	World Geodetic System 1984

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ORIGINAL RESEARCH PAPER

Spatial prediction of the number of wildfire hotspots using negative binomial conditional autoregressive random forest

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ABSTRACT

BACKGROUND AND OBJECTIVES: Predicting the spatial distribution of wildfire hotspots is crucial for forest fire mitigation, particularly in high-risk regions such as Kalimantan Island, Indonesia. Hotspots are defined as locations where thermal anomalies are present, surpassing the usual background temperature. An integrated framework is proposed: a negative binomial conditional autoregressive random forest. The approach is designed to capture nonlinearity in meteorological drivers, over-dispersion in the number of hotspots, and spatial dependence among neighboring grid cells. This study aims to estimate the number of hotspots and to pinpoint the meteorological factors that significantly affect the emergence of hotspots.
METHODS: The number of hotspots in Kalimantan for September 2024 were analyzed on a grid. Predictors included air temperature, precipitation, relative humidity, wind speed, and dry days. These variables were aggregated into spatial grids with a resolution of 0.25 degree by 0.25 degree. The study conducted a simulation where the levels of spatial autocorrelation, alternative spatial weight matrices, the ratios of predictor variance to spatial residual variance, and sample sizes were modified. Model performance was evaluated using root mean square error and mean absolute error.
FINDINGS: The proposed model consistently outperformed the conventional conditional autoregressive model in both simulated and empirical datasets. Gains were largest when predictor variance exceeded spatial residual variance. Across most scenarios, reductions in root mean square error by 24 percent and in mean absolute error by 33.3 percent were observed. It was observed that the results remained stable when alternative spatial weight matrices were applied. In the empirical application, the model accurately predicted the spatial distribution of hotspots. Overestimation occurred in approximately 21.43 percent of the grid cells of the observed. Air temperature and relative humidity emerged as the leading predictors, but their relative significance changed across distinct spatial clusters. Meteorological effects were weaker in wet, humid clusters and stronger in hot, dry clusters.
CONCLUSION: Practical accuracy improvements for spatial prediction of the number of hotspots are generated by the integrated framework. It is advisable to integrate into operational early-warning systems and decision support mechanisms for the prevention of forest and land fires in tropical areas susceptible to fires.

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45	9	3

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INTRODUCTION

The swift expansion of geospatial data has revolutionized environmental analytics, as the spatial interdependence between locations undermines the assumptions of independence (Dumelle *et al*., 2023; Lee and Mitchell, 2013; Pebesma and Bivand, 2023). The neighborhood structure and spatial dependence are represented by conditional autoregressive (CAR) and intrinsic CAR (ICAR) models (Griffith, 2025; Lee and Mitchell, 2013). CAR and ICAR are widely used across environmental applications, including small-area disease mapping where neighborhood-based random effects explicitly capture spatial autocorrelation (Porter *et al*., 2024; Tessema *et al*., 2023). Disregarding spatial autocorrelation has been demonstrated to skew estimates and diminish accuracy (Yang *et al*., 2021). Nevertheless, many real-world predictor–response relationships remain nonlinear and complex. Random forest (RF) addresses such settings with minimal distributional assumptions, tolerance to multicollinearity, and explicit variable importance (Breiman, 2001; Hu and Szymczak, 2023; Lin *et al*., 2023; Nie *et al*., 2024). RF is a flexible, nonparametric ensemble that models complex nonlinear relationships, typically achieves high predictive accuracy, and requires minimal tuning (Elsayad *et al*., 2025; James *et al*., 2013; Segal and Xiao, 2011). In applications related to wildfires, RF has frequently surpassed standard machine-learning benchmarks for predicting susceptibility and events across various ecoregions and seasons (Bustillo Sánchez *et al*., 2021; Pascolini-Campbell *et al*., 2025; Trucchia *et al*., 2022). The phenomenon of hotspots is critical in wildfire mitigation. In this study, wildfire hotspots are locations with thermal anomalies above normal background temperature (Giglio *et al*., 2003). Recognizing and anticipating the quantity of hotspots is vital as the occurrence of wildfires escalates with climate change; meteorological elements such as precipitation, temperature, and humidity have a strong impact on hotspot variability (Abatzoglou *et al*., 2025; Grillakis *et al*., 2022; Jones *et al*., 2022; Lan *et al*., 2021; Sanderson and Fisher, 2020; Shmuel and Heifetz, 2022; Zhu *et al*., 2022; Ibrahim *et al*., 2024). Despite these advances, methodological gaps remain. Conventional CAR models typically assume an additive linear predictor and are most often paired with Poisson or Gaussian likelihoods (Coly *et al*., 2021; Wang *et al*., 2024). Conversely, standard random forest (RF) does not account for residual spatial autocorrelation, which can degrade predictive accuracy and bias inference when outcomes cluster spatially (Milà *et al*., 2024; Saha et al., 2023). Recent spatial machine-learning variants, such as geographical random forest (GRF) and geographically weighted random forest (GWRF), introduce local weighting and spatial heterogeneity within tree ensembles, while spatial autoregressive random forest (SPAR-forest) augments RF with spatial autoregressive (SAR) or CAR components (Georganos *et al*., 2021; Macbride *et al*., 2025; Wang *et al*., 2024). These models are mainly structured for continuous outcomes under Gaussian assumptions and, as of now, to date, do not jointly accommodate negative binomial (NB) count over-dispersion with residual spatial autocorrelation within a single framework. For environmental monitoring with count responses, over-dispersion is common, so NB formulations are often preferable to Poisson models (Agresti and Kateri, 2022; Cameron and Trivedi, 1998). A negative binomial conditional autoregressive random forest (NBCAR-Forest) is proposed. The framework combines a negative binomial distribution for counts with a CAR component, which helps to account for residual spatial dependence, while still maintaining the nonlinear and interaction-rich mapping characteristics of RF. This integration is designed to improve prediction when hotspot counts are over-dispersed and spatially clustered and when meteorological effects are nonlinear. Kalimantan, Indonesia, is adopted as the empirical setting because wildfire risk there is recurrent, linked to hydro-climatic variability, and amplified by extensive, fire-prone peat landscapes (Graham *et al*., 2024; Heo *et al*., 2023; Schmidt *et al*., 2024). These conditions exemplify tropical zones where hotspot-driven prevention is essential for operational success. The number of hotspots in Kalimantan follows a NB distribution (Rohimahastuti *et al*., 2025). Recent studies in Indonesia have leveraged satellite hotspots with machine learning for risk mapping, yet over-dispersion in counts and residual spatial dependence are often addressed only partially. It is typically via Poisson or Gaussian assumptions and without an explicit CAR component (Ardiyani *et al*., 2023; Heo *et al*., 2023; Kadir *et al*., 2023; Karurung *et al*., 2025). The analysis targets monthly the number of hotspots at a moderate spatial resolution using precipitation, temperature, relative

humidity, wind speed, and dry days. This study offers two significant contributions. The first is the creation of a unified NBCAR-forest that effectively manages over-dispersion in hotspot numbers, accounts for residual spatial autocorrelation among neighboring grid cells, and incorporates nonlinear effects of predictors. Second, empirical utility is demonstrated in Kalimantan through spatial prediction and variable-importance analysis that are directly relevant to risk mitigation and resource allocation. Together, these advances aim to make the number of hotspots predictions more reliable for operational forest fire management in tropical environments. Furthermore, the strategy aligns with sustainable development goal 13 (SDG 13: Climate Action) by delivering a scientific framework for hotspot forecasting, mitigation efforts, and spatial management. This study aims to predict the number of hotspot occurrences in Kalimantan, Indonesia, by integrating spatial modeling techniques with machine learning approaches. This study was conducted in Kalimantan, Indonesia in 2024.

MATERIALS AND METHODS

Hotspot data are essential for monitoring wildfires, which significantly impact the environment, economy, and public health. Land clearing, peatland degradation, extreme weather conditions, or anthropogenic activities often cause these fires. Precise forecasting of hotspot events can support wildfire prevention initiatives and efficiently distribute resources for mitigation. The island of Kalimantan was divided into spatial units using a grid system, with each unit representing a specific area defined by geographic boundaries. This grid-based framework supports the assessment of how hotspots are spatially distributed and their interactions with meteorological variables. The study aims to anticipate the occurrence of hotspots by analyzing a range of climatic factors.

Response variable

The response variable in this study is the number of hotspot occurrences in each spatial unit. Hotspots were derived from satellite thermal anomalies detected by visible infrared imaging radiometer suite (VIIRS) and MODIS with day- and night-time acquisitions. Detection is unavailable where cloud covers or a blank zone. The dataset spans September 2024 and was obtained from BMKG in NetCDF format at 0.25° × 0.25° resolution. The BMKG reports confidence levels on a scale of 0–100—low (0–29), medium (30–79), and high (80–100). An elevated confidence percentage for a hotspot implies a greater chance of it being a forest or land fire. However, the criterion for a hotspot is exceedance of normal background temperature in satellite data, not the map scale. No supplementary confidence thresholding was applied; independent ground-based validation was not present and is acknowledged as a limitation, with provider confidence being used as a stand-in for reliability. Fig. 1 presents the study area map of Kalimantan Island. As shown in Fig. 2, the intensity of hotspot occurrences was highest in September 2024. Therefore, this study selected September 2024 as the period of analysis.

Predictor variables

Many meteorological and environmental variables were used to predict the number of hotspots in each spatial unit, as they are presumed to influence wildfire occurrence significantly. Data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and Copernicus were harmonized to monthly aggregates on a 0.25° × 0.25° grid to match the hotspot dataset. A grid resolution of 0.25° was selected to achieve a balance in mesoscale meteorological representation, align with monthly ERA5 products, and maintain computational efficiency within the NBCAR-Forest pipeline. The variables included monthly average total precipitation meter (m), the number of dry days per month, defined as days with precipitation below 0.001 m, monthly average 2-m air temperature (K), monthly average wind speed at 10 meter (meters/second), and monthly average relative humidity in percent (%). The ECMWF Re-Analysis 5th Generation (ERA5) monthly averaged datasets provided data on precipitation, temperature, wind speed, and humidity, while the analysis assessed dry days based on ERA5 Hourly Data. The predictors were different in terms of scale and units. All variables were standardized to a zero mean and unit variance before modelling. Monthly-averaged ERA5 products for precipitation, temperature, relative humidity, and wind speed were used directly. “Dry days” were derived from ERA5 hourly total precipitation. Hourly values were aggregated to daily totals per grid cell, then counted as monthly days with daily rainfall < 0.001 m. The ERA5 0.25° grid and the hotspot grid

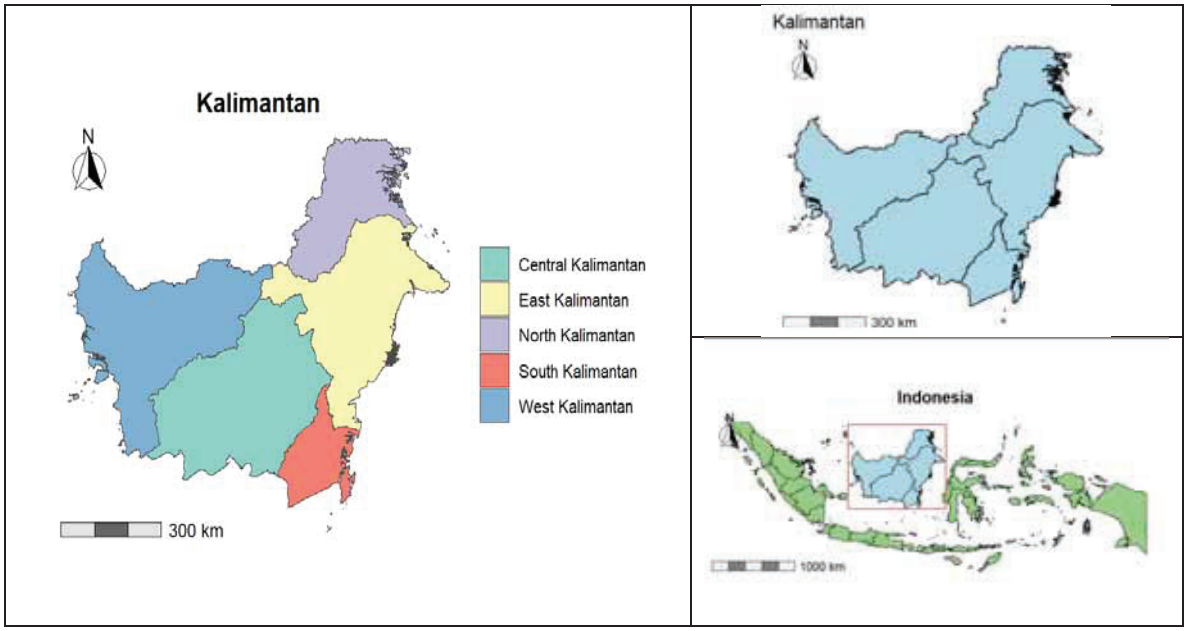

Fig. 1: Geographical location of the study area map of Kalimantan, Indonesia

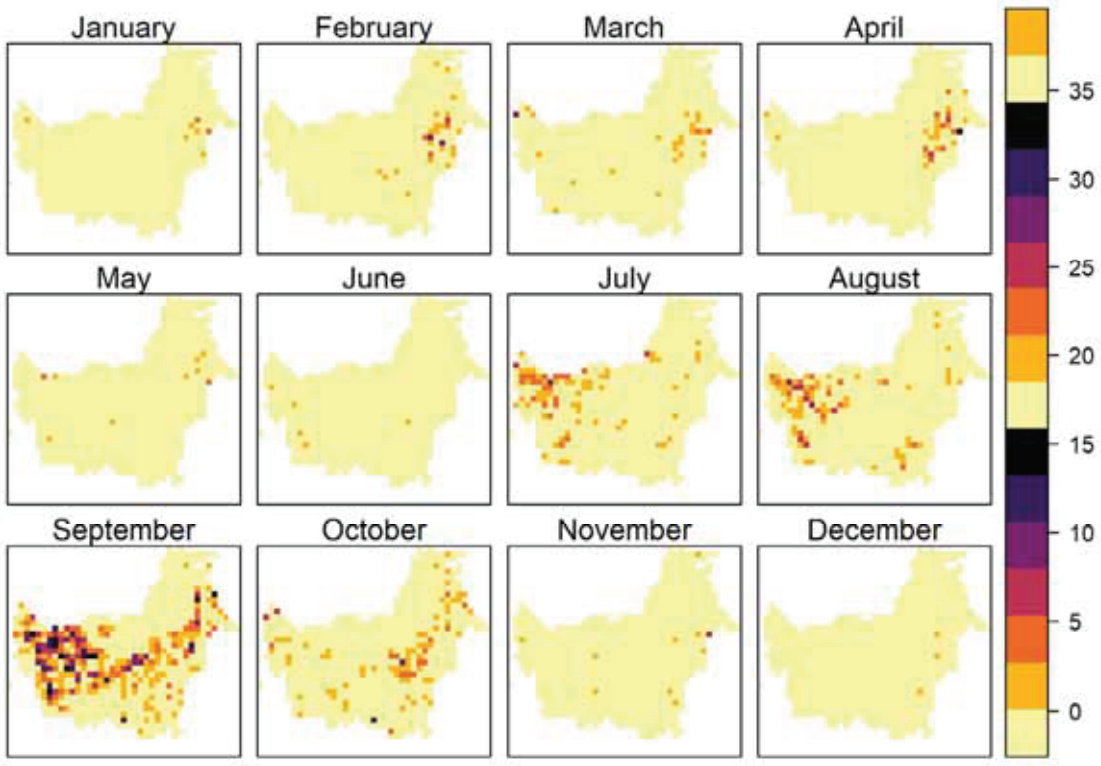

Fig. 2: Monthly hotspot intensity in Kalimantan, 2024

are coincident. The verification of alignment was achieved by matching the center coordinates of the grid cells; there was no need for spatial resampling. No additional data-quality screening or independent validation was conducted beyond the ECMWF/ERA5 production pipeline. Essential physical range assessments were executed (for instance, relative humidity from 0–100%, precipitation ≥ 0, wind speed ≥ 0, temperatures within plausible bounds), with no discrepancies that required imputation.

Methods

The methodology of this study consisted of two main stages: prediction using simulated data and application of the NBCAR-Forest model to empirical hotspot occurrence data. The simulation study integrated different scenarios to supplement the empirical analysis and deliver a more complete understanding of the phenomenon in question, particularly to assess the accuracy of the model's predictions. Simulation settings were chosen to reflect realistic wildfire patterns in Kalimantan. The elements of the simulation study are detailed in the following sections:

1. Determining the number of observations (n), n = (700, 1200, 2500). The analysis opted for this parameter to measure model performance across datasets with varying sizes. Larger values of n increase the computational complexity of the model, so considering different dataset sizes allows assessment of the model's scalability and efficiency. This selection represents feasible counts of 0.25° grid cells within the study area, ensuring that the lattice structure and boundary conditions correspond to the empirical environment.

2. Generating regular spatial coordinates in a grid format. Subsequently, the analysis established spatial connectivity among points using the Queen contiguity method, which automatically connects each point to all neighboring points, including diagonal neighbors. This approach consistently and systematically depicts local spatial relationships in line with the created grid structure. This method is used because it is in accordance with empirical data in the form of a regular grid. Fig. 3 ilustrares the grid generation pattern for simulation.

3. Determining the spatial autoregressive coefficient, ρ = (weak 0–0.5, moderate 0.6–0.8, strong 0.9–0.99). The range of ρ spans weak to strong dependence while remaining within the admissible set that guarantees a valid precision matrix. As the value of ρ increases, the spatial relationship among data points becomes stronger. Generating two explanatory variables (X_1 and X_2) based on a bivariate uniform distribution (0, 2π). Subsequently, multicollinearity is checked using the Variance Inflation Factor (VIF), with the criterion that VIF values should not exceed 10.

4. Random-forest hyper parameters were tuned using spatial block cross-validation on the 0.25° grid. Candidate sets were m_{try} (the number of randomly selected predictors at each tree split) is set as $m_{try} = (1,3,5)$. Meanwhile, min_{node} (the minimum number of observations in a terminal node) is set as $min_{node} = (1,5,10)$, aiming to produce a simpler tree structure that reduces overfitting risk, though it may

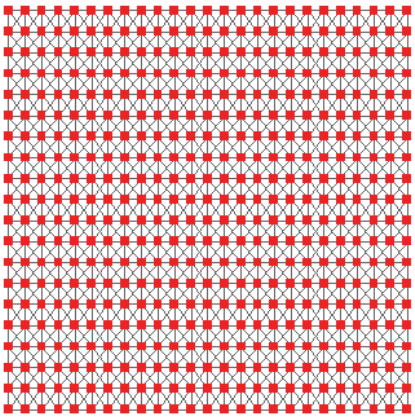

Fig. 3: Grid generation pattern for simulation

affect prediction accuracy. The number of trees in the forest is set at 1,000.

5. The relationship pattern between explanatory variables is set to be nonlinear.

6. Following the guidelines of Macbride *et al.* (2025), simulation scenarios were formulated and comprise three different contexts. Scenarios were constructed to assess model sensitivity. Var(X)/Var(ϕ) spanned covariate-dominated, balanced, and spatial-residual-dominated regimes, representing shifts between meteorological control and unmeasured spatial drivers.

Scenario 1:

A nonlinear relationship is specified between the feature variables and the response, using the function $\left(1.5\,sin\left(X1\right)+log\left(X2+0.5\right)\right)$ with the variance of the spatial random effect selected so that the standard deviations of the features and the spatial effect are approximately equal ($Var\left(x\right)\approx Var\left(\phi\right)$). This indicates an equitable contribution from the feature variables alongside the spatial random effect in shaping the response value.

Scenario 2:

The nonlinear function is set as $\left(2\,sin\left(X1\right)+log\left(X2+0.5\right)\right)$, but the variance of the spatial effect is chosen so that the features are more dominant; the standard deviation of the features is twice as large as that of the spatial effect ($Var\left(x\right)>Var\left(\phi\right)$). This suggests that the features are prioritized over the spatial random effect in terms of predicting the response.

Scenario 3:

A nonlinear relationship with a smaller coefficient, $\left(0.5\,sin\left(X1\right)+log\left(X2+0.5\right)\right)$, is applied, while the variance of the spatial effect is set to be higher so that the standard deviation of the features is only half that of the spatial random effect ($Var\left(x\right)<Var\left(\phi\right)$). In this context, the spatial random effect takes precedence over the features in influencing the response.

7. The response variable Y is generated using a spatial CAR model with a Negative Binomial response distribution, using Eq. 1 (Besag, 1974):

$$Y = X\beta + C\left(Y - X\beta\right) + \varepsilon \tag{1}$$

The spatial correlation matrix is defined as $C = B + B' - BB'$ where $B = \rho W$ and W denote the spatial weights matrix. The design matrix X is composed of an intercept column (a column filled with ones) along with columns that represent the predictor variables incorporated in the model. Specifically, if there are m predictor variables, then X is an $n \times \left(m+1\right)$ matrix structured, using Eq. 2 (Lee and Mitchell, 2013):

$$X = \begin{bmatrix} 1 & X_{11} & \dots & X_{1m} \\ 1 & X_{21} & \dots & X_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & X_{n1} & \dots & X_{nm} \end{bmatrix} \tag{2}$$

The parameter vector β has dimension $\left(m+1\right)\times 1$, containing the intercept β_0 and regression coefficients $\beta_j, j = \left(1,2,\dots,m\right)$. The joint distribution of Y is characterized by the conditional probability $Y \sim N\left(\mu, \left(I-C\right)^{-1}M\right)$, where $\left(I-C\right)$ is invertible, symmetric, and positive definite. Here $Y = \left(Y_{(S_1)},\dots,Y_{(S_n)}\right)'$ is the response vector, $C = \left(c_{ij}\right)$ is an $n \times n$ matrix, and $M \equiv diag\left(\sigma_1^2,\dots,\sigma_n^2\right)$ is a diagonal matrix of size $n \times n$. For the purposes of estimation and prediction, the observation model employed is a negative binomial that incorporates a latent spatial random effect; the autoregressive structure presented in Eq. (1) is exclusively utilized to produce spatial covariance during the simulation study. A link function is used to specify the mean: $\mu = \exp\left(X\beta + \phi\right)$, where $\phi \sim N\left(0, \left(I-C\right)^{-1}M\right)$ denotes the spatial random effect, and $Y \sim NB\left(\mu,\theta\right)$ is the response generated from an NB distribution with dispersion parameter θ.

The NBCAR-forest algorithm applied here is based on the SPAR-Forest algorithm (Macbride *et al.*, 2025) and the CAR model of Lee and Mitchell (2013), with the following modifications: The decorrelated variable is defined as $Z\left(A_k\right) = \log\left(Y\left(A_k\right)+0.5\right) - \phi\left(A_k\right)$, where A_k denotes the k-th location with $k = 1,2,\dots,K$, and the model employs the NB distribution: $\hat{Y}\left(A_k\right) \sim NB\left(\mu\left(A_k\right),\theta\right)$ where $\mu\left(A_k\right) = \exp\left(\hat{m}\left[x\left(A_k\right)\right] + \phi\left(A_k\right)\right)$ and $\phi\left(A_k\right)$ is estimated using the CAR model. Five spatial weighting matrices are considered: Delaunay triangulation (TD), K-Nearest Neighbor (KNN, K=5), Queen contiguity, Rook contiguity, and inverse distance (INV). The design quantifies the impact of W misspecification

on RMSE and residual Moran's I. For empirical analysis, global Moran's I on raw counts and RF residuals indicates residual spatial autocorrelation, which drives the CAR component. The principal W is selected according to the simulation outcomes. The NBCAR-forest algorithm (A modification of SPAR-Forest algorithm (Macbride *et al*., 2025)) is detailed as follows:

Step 0:

Parameter Initialization. Set the tuning parameters, such as the number of samples (n), minimum node size (min_{node}), number of predictors per split (m_{try}), spatial dimension (D), and number of iterations (R). Initialize the spatial random effect $\phi(A_k)=0$ for all spatial units $k=1,2,\ldots,K$.

Step 1:

Iterative Fitting Procedure (Repeat for $r=1,\ldots,R$).

Stage A: Calculate the decorrelated variable for each spatial unit $Z(A_k)=\log(Y(A_k)+0.5)-\phi(A_k)$ where $Y(A_k)$ is the observed count data (assumed NB) and $\phi(A_k)$ is the spatial random effect from the previous iteration.

Stage B: Fit RF model on the training data, using predictor variables $x(A_k)$ and $Z(A_k)$. Obtain out-of-bag predictions and predictions for the test data; denote these predictions as $\hat{m}\left[x(A_k)\right]$.

Stage C: Fit a spatial random effect model based on the CAR structure on the training data using integrated nested laplace approximation (INLA) for computational efficiency, with RF predictions included as a fixed offset using Eq. 3 (Macbride *et al*., 2025; Lee and Mitchell, 2013). The computational advantages of INLA relative to alternative approaches are documented in Macbride *et al*. (2025).

$$\hat{Y}(A_k)\sim NB(\mu(A_k),\theta),\ \log(\mu(A_k))=\hat{m}\left[x(A_k)\right]+\phi(A_k) \quad (3)$$

Where, the $\phi(A_k)$ followed a CAR prior on graph W , the NB dispersion θ was estimated under default weakly-informative priors. Explanation Eq. 3:

$\hat{m}\left[x(A_k)\right]$ is the prediction from RF.

$\phi(A_k)$ is the spatial random effect.

$\mu(A_k)$ is the expected value under the NB distribution.

θ is the dispersion parameter.

The posterior estimate of $\phi(A_k)$ is computed and used to update the spatial random effect for the next iteration. Model formula with offset, prior on $\phi(A_k)$, dispersion θ, and convergence criterion based on R.

Step 2:

Final prediction; after R iterations, use the CAR model from the final Step C to produce final predictions for the test data.

In summary, the study methodology can be seen in the flow of Fig. 4.

RESULTS AND DISCUSSION

This section outlines the outcomes of applying the NBCAR-Forest model, which was assessed using both simulated and real-world data. The assessment process initiates with simulation studies intended to measure the model's effectiveness in predicting the number of hotspots in various scenarios, and is subsequently applied to real hotspot data from Kalimantan in September 2024. The predictive performance of NBCAR-Forest is compared to the Negative Binomial Conditional Autoregressive (NBCAR) model without Random Forests, using RMSE and MAE as performance indicators. The simulations are conducted under fixed parameter settings such as $\theta=10$, R=5, D=5, $inla_{samples}$=100, n_{tree}=(700,1200,2500), and three levels of spatial dependence (ρ_{low}=0.6, ρ_{medium}=0.8, ρ_{high}=0.95), resulting in a total of 270 simulation scenarios. Specifically for the selection of mtry and min_{node}, a spatial block cross validation was performed. The optimal m_{try} and min_{node} for simulation and empirical purposes are 1 and 5, respectively. Fig. 5 presents the RMSE and MAE results for three principal scenarios (n=700, 1200, 2500), with ρ =(low, medium, high), three scenarios of variance, and all adjacency matrices for single repetition.

Fig. 5 illustrates the assessment of model performance derived from simulation outcomes, contrasting RMSE and MAE across all simulation scenarios. The columns illustrate RMSE and MAE; the rows in each panel contrast the NBCAR baseline against the NBCAR-Forest. Three overarching patterns can be identified. First, in most scenarios, NBCAR-Forest demonstrates reduced errors compared to NBCAR (lighter tiles), suggesting improvements from capturing nonlinear effects while maintaining a spatial aspect. Second, errors decrease with larger

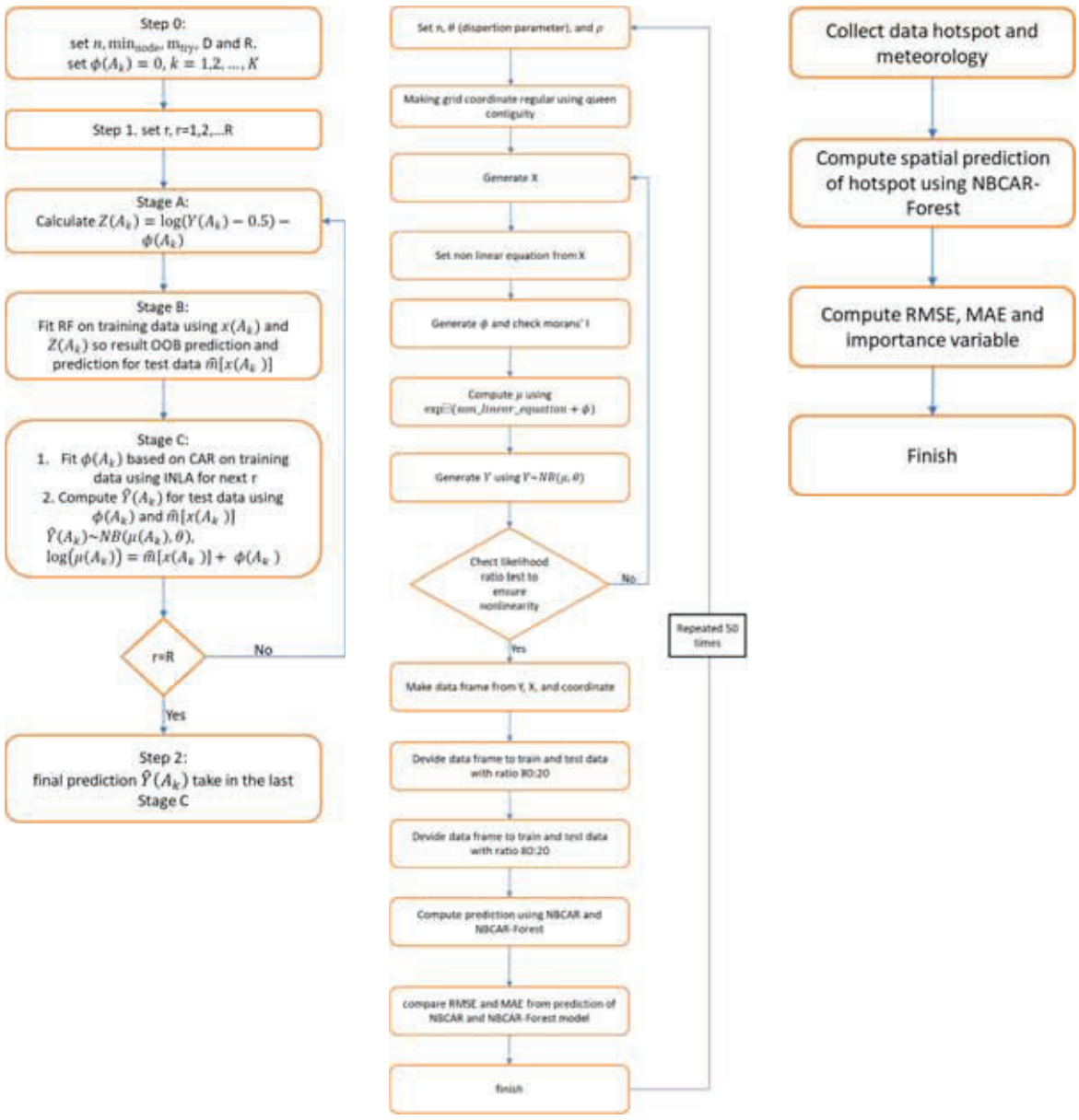

Fig. 4: Panels of the simulation (a), empirical workflow (b) and NBCAR-Forest algorithm (c)

n, visible as a left-to-right lightening from n = 700 to n = 2500; this improvement is more pronounced for NBCAR, narrowing—but not eliminating—the performance gap. Third, stronger spatial dependence (ρ_{high}) is associated with larger errors, especially at small n, while Low ρ settings are consistently weaker (lighter tiles). Across variance regimes, predictive error is smallest when Var(X) > Var(ϕ) and largest when Var(X) < Var(ϕ); as unexplained spatial variability becomes dominant, both RMSE and MAE heatmaps darken, indicating reduced identifiability of covariate effects. The variations between W schemes are minor when compared to the impacts of model selection, n, and ρ; no particular scheme

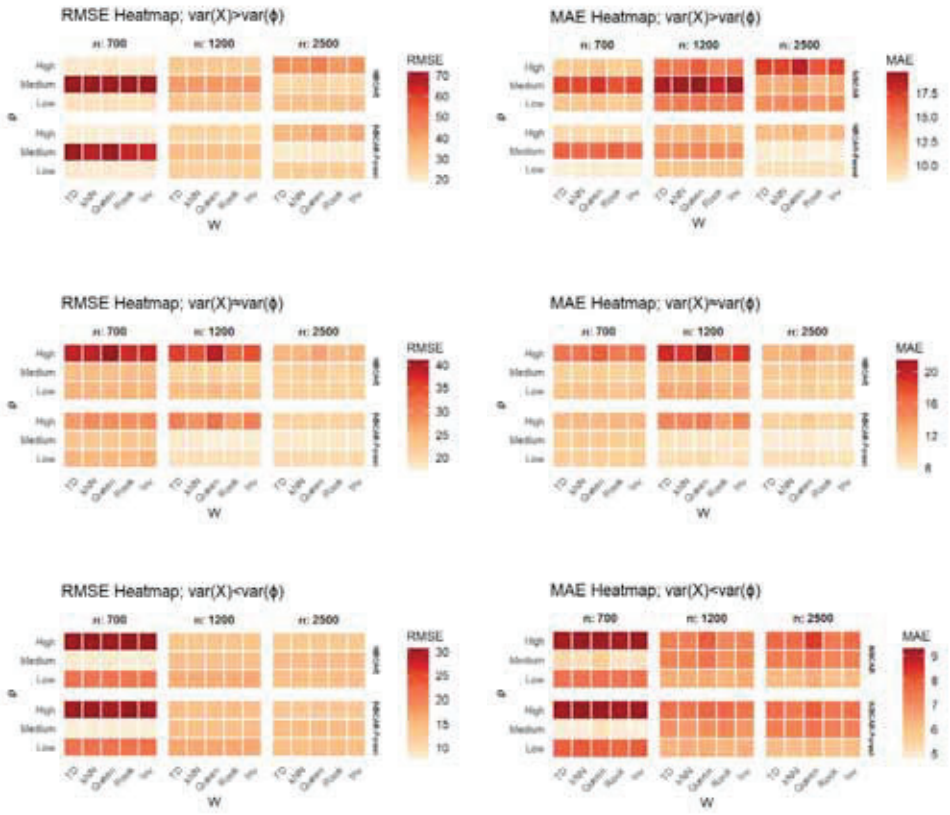

Fig. 5: Heatmaps of RMSE/MAE across **ρ**, n, variance regimes, and W for single repetition

prevails in every panel. RMSE and MAE convey the same qualitative conclusions. NBCAR-Forest provides more accurate predictions across a wide range of spatial and variance conditions, with the largest gains under strong spatial autocorrelation and smaller samples. These conclusions support the idea that the integration of RF within the NBCAR framework boosts prediction accuracy for hotspot counts, maintaining stable performance regardless of sample size variations. However, NBCAR-Forest presents a limitation in Step 1: increasing R does not always lead to improved model performance. Therefore, in Step 1, the value of R that produces the lowest RMSE and MAE is selected, and this optimal result is then used for Step 2 of the NBCAR-Forest algorithm. Furthermore, this analysis carries out repeated simulations with 50 replications, employing R = 5 to maintain consistency. For every iteration, the R that results in the lowest RMSE and MAE is selected to represent the optimal model performance given the defined simulation condition. This strategy ensures a more stable and robust model selection when objectively evaluating the NBCAR-Forest method. Average of RMSE and MAE of 50 repetition can be seen in Fig. 6.

Fig. 6 presents heatmaps of average RMSE and MAE over 50 repetitions, stratified by variance regime, n, ρ, W, and models (NBCAR vs. NBCAR-Forest). Across most scenarios, NBCAR-Forest reduced RMSE by 24% and MAE by 33.3% relative to NBCAR. Lower average errors are achieved by NBCAR-Forest relative to NBCAR across most configurations, with the largest reductions under High ρ and smaller n. With an increase in n, the error magnitudes diminish, leading to lighter tiles arranged from left to right within each column of the panel. A clear gradient in ρ is evident: higher ρ yields larger errors, medium ρ yields intermediate errors, and low ρ yields the smallest errors. Across variance regimes, errors are lowest when Var(X) > Var(ϕ), intermediate

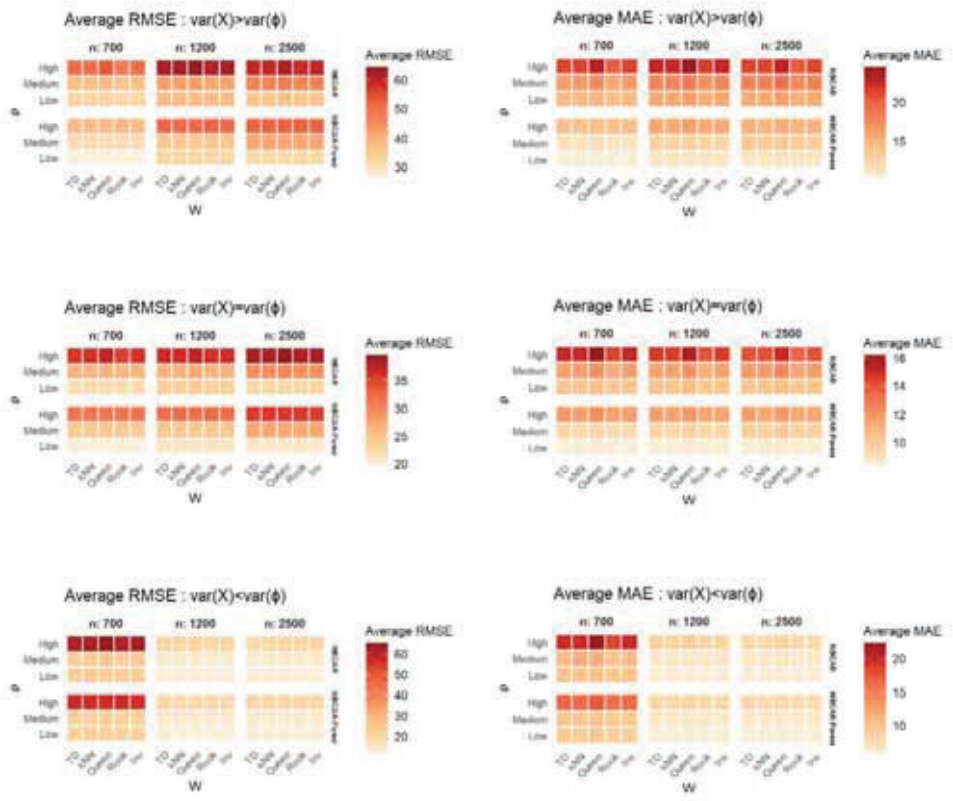

Fig. 6: Heatmaps of mean RMSE/MAE across ρ, n, variance regimes, and W for 50 repetitions

when Var(X) = Var(ϕ), and highest when Var(ϕ) > Var(X). Differences across W are modest relative to effects of models, n, ρ, and variance regime. The data reveals that, on average, NBCAR-forest reliably delivers lower RMSE and MAE than NBCAR in every simulation scenario. The improvement in NBCAR-Forest performance is most pronounced in challenging scenarios such as high ρ, where the error margin compared to NBCAR reaches over 10 points for RMSE and 6–9 points for MAE. ρ is the dominant factor under our simulation design. Next, the Kruskal Wallis test and the pairwise Wilcoxon test with Bonferroni correction were carried out. Across most model–metric combinations, the results of Kruskal–Wallis tests reveal no significant impact of sample size n on performance (p>0.05), apart from a few isolated exceptions. Stratifying by ρ yields significant omnibus differences in all scenarios (p<0.05), prompting pairwise Wilcoxon tests with Bonferroni correction. These post hoc results indicate that the "high" group differs significantly from both "low" and "medium" (p<0.005), whereas "low" vs. "medium" is not different (p=0.202). Implication: emphasis should be placed on high-ρ settings, while "low" and "medium" can be treated similarly in modeling strategies. In the scenarios analyzed, NBCAR-Forest typically surpasses NBCAR, though the extent of this advantage differs based on the degree of spatial autocorrelation, neighborhood configuration, and sample size. NBCAR-forest appears promising for hotspot analysis in heterogeneous regions; however, further evaluation against additional strong baselines would be valuable before making broader generalizations. A systematic comparison was performed to investigate a specific question: does the incorporation of a random-forest mean function within an NB-CAR framework enhance predictive accuracy? The present study does not make broader claims regarding other advanced learners, since evaluating those families is beyond its scope; such extensions would allow for more comprehensive benchmarking in future studies.

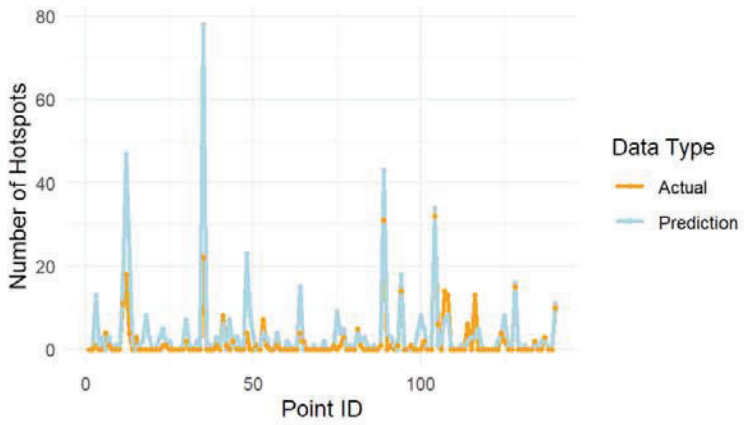

Fig. 7: Predicted vs observed counts
(Kalimantan, Sep-2024, 0.25° grid, N=696; 80:20 split; CAR weights = kNN-5)

Empirical study on hotspot data

Following the simulation-based validation, the NBCAR-Forest model was applied to predict the number of hotspots in Kalimantan for September 2024, using data from BMKG and ECMWF. The meteorological predictor variables were arranged into a 0.25° × 0.25° spatial grid, resulting in 696 grid cells across the study area. The dataset was split into training and testing subsets with an 80:20 ratios. The number of hotspots and predictor variables, mapped to their respective grid cells, was used for model training with NBCAR-Forest. Model performance was evaluated on the test set, using RMSE and MAE as indicators. On the held-out test set, the model achieved RMSE and MAE of 6.54 and 2.60, respectively. Fig. 7 depicts the comparison of the predicted number of hotspots against the observed number.

Fig. 7 demonstrates that the model predictions overestimate the actual number of hotspots. Forecasts often surpass the actual counts in certain sub-regions, suggesting a consistent tendency to overestimate. Two mechanisms are plausible under a meteorology-only specification. First, zero inflation: many grid cells contain no hotspots, while meteorological conditions alone may be sufficiently conducive to fire, yielding positive predicted counts. Of the 696 grid cells, there are 460 grids that have a value of zero. With an aggregate bias ratio of 0.936, it indicates that the predicted counts are roughly 93.6% greater than the observed counts in total. Although the error magnitudes are RMSE = 6.54 and MAE = 2.60. Second, omitted anthropogenic drivers: ignition and spread are mediated by human activity (e.g., access and land use); in the absence of such covariates, elevated risk may be assigned to meteorologically favorable yet human-inactive areas. This is consistent with the observations of Karurung *et al*. (2025), who highlighted that human activities and changes in land cover are major contributors to hotspots. Consistent with these mechanisms, residual maps display spatially coherent positive residuals, and residual Moran's I remains significant, indicating structure not captured by meteorology alone (Moran's I=0.92, p=0.00). By design, meteorological controls were isolated, yet localized overestimation persists—consistent with the lack of anthropogenic proxies. Operational bias mitigation—without modifying the model or introducing new covariates—comprises two post-processing steps: (i) cluster-wise mean-bias adjustment, obtained by subtracting each cluster's average residual from the corresponding predictions; and (ii) monotonic (binned) calibration that rescales predictions by the ratio of observed to predicted means within deciles of $\hat{Y}$ to improve upper-tail calibration in zero-heavy cells. The original metrics are kept intact to avoid confusing modeling with post-hoc calibration, and thorough implementation procedures are outlined to ensure reproducibility and future operational use. Incorporation of accessibility and land-use variables will be prioritized when such data are available. Future extensions will incorporate proxies for human pressure and accessibility (distances to roads,

canals, and settlements; nighttime lights; land-cover fractions; peat depth; and concession boundaries) to more directly represent ignition and spread potential. The primary variables impacting hotspot occurrences in Kalimantan in September 2024 are determined based on the variable importance values detailed in Table 1.

Table 1 presents the variable importance values derived from the NBCAR-Forest model for predicting the number of hotspots. The importance of variables quantifies the impact of each predictor in minimizing model prediction errors, demonstrating the degree to which each variable clarifies the observed fluctuations in hotspot occurrences. A higher importance value indicates a more substantial influence on the predicted number of hotspots. As indicated in Table 1, air temperature was identified as the primary predictor (importance = 70.33), underscoring its essential influence on the number of hotspots throughout the study period. This finding is physically plausible, as elevated air temperatures enhance the risk of forest and land fires by increasing fuel flammability. The most significant variables are relative humidity (52.86), wind speed (43.64), and the total number of dry days (40.51). Decreased relative humidity speeds up fuel drying and lowers moisture levels, which raises the likelihood of ignition; therefore, dry air is generally linked to a higher number of hotspots. High wind speeds can accelerate the spread of fires, while extended periods without rainfall sustain dry conditions that favor the formation. Total precipitation (38.73) contributed little. Higher rainfall is typically associated with fewer fires: rainfall moistens and cools fuels, increases ambient humidity, and promotes evaporative cooling, which lowers near-surface temperatures and ignition potential, thus reducing ignition and spread. The findings suggest that meteorological elements, particularly air temperature, relative humidity, and wind speed, play a crucial role in predicting prediction. These findings are consistent with prior studies reporting similar meteorological controls on fire activity. Grillakis *et al*. (2022) report that high temperatures, strong winds, and prolonged dry spells primarily drive the global frequency and severity of fire weather events. Likewise, Jones *et al*. (2022) point out that the key elements leading to an increase in fire risk around the world are warmer, drier, and windier weather conditions. In Asia, Zhu *et al*. (2022) identify high air temperature, strong winds, and persistent drought as the main factors responsible for the occurrence and spread of forest fires, particularly in Yunnan Province. According to Lan *et al*. (2021), maximum temperature, wind speed, and the total of consecutive dry days significantly affect fire risk, with dry days being particularly vital. Additionally, through machine learning analysis, Sapkota *et al*. (2025) confirm that rising temperatures, higher wind speeds, and prolonged dry periods are the main predictors of wildfire events. Conversely, precipitation and humidity are more directly linked to a decrease in fire risk.

Further analysis of empirical data

As shown in Fig. 7, Predictions tend to exceed observed counts, indicating systematic overestimation in parts of the domain. An in-depth review of the empirical data was undertaken to confront this challenge and boost predictive precision. The dataset was segmented using spatial clustering based on geographic coordinates (location) and the number of hotspots. By grouping spatial units with comparable hotspot characteristics, this clustering technique decreases prediction variance. The results of the clustering analysis are presented in Fig. 8.

As illustrated in Fig. 8, Map of three clusters derived from geographic location and hotspot intensity, used to reduce within-cluster variance and explore heterogeneity across space. Moran's I indicates global spatial autocorrelation; values of

Table 1: Variable importance

Variable	Importance values
Precipitation	38.73
Relative humidity	52.86
Dry days	40.51
Wind speed	43.64
Air temperature	70.33

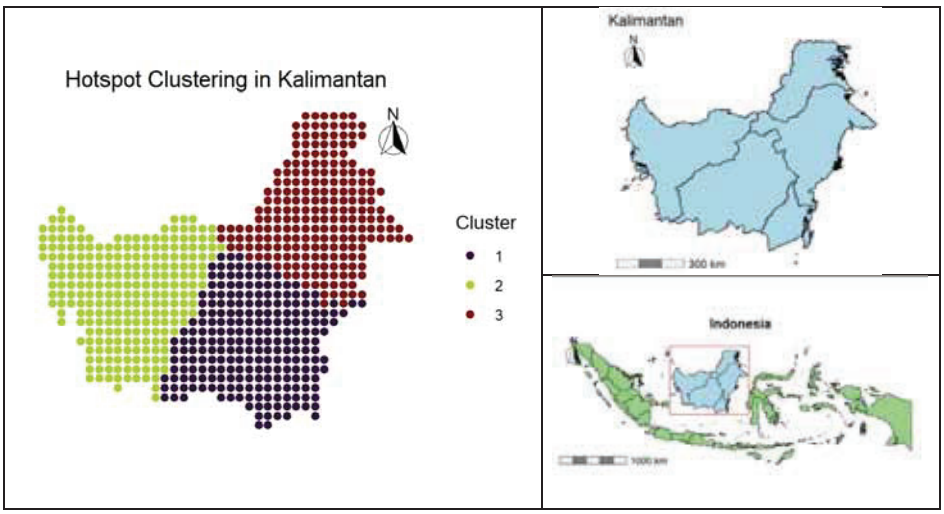

Fig. 8: Spatial clustering of number of hotspots in Kalimantan, Sep. 2024

0.47 (Cluster 2), 0.28 (Cluster 1), and 0.10 (Cluster 3) were observed (all $p<0.01$). This implies that the distribution of hotspots across Kalimantan is not completely arbitrary, but instead exhibits noticeable spatial groupings in particular locations, especially where hotspot density is high. The RMSE and MAE values for NBCAR-Forest modeling in Clusters 1, 2, and 3 are presented in Table 2.

Table 2 presents the performance evaluation results of the NBCAR-Forest model for each cluster using two primary metrics: Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). Both metrics analyze the model's ability to predict the number of hotspots in each cluster, with lower values denoting enhanced performance. In Cluster 1, the NBCAR-Forest model achieved the best predictive performance, with an RMSE of 2.11 and an MAE of 1.02. Cluster 1 yielded the lowest errors among clusters, while errors were higher in Cluster 2 and intermediate in Cluster 3. In Cluster 2, the model yielded an RMSE of 5.88 and an MAE of 2.92, indicating higher error than Cluster 1 and suggesting that the model faces greater challenges in predicting the number of hotspots in this cluster. This could be due to more intricate spatial variations, an increased number of hotspots, or distribution patterns that the model fails to completely account for. For Cluster 3, the RMSE and MAE were 3.69 and 1.66, respectively. Although the model's performance in Cluster 3 is better than in Cluster 2, it is still less accurate than in Cluster 1. The unique spatial features and the arrangement of hotspots within each cluster probably affect the variations in predictive accuracy among the clusters. Subsequently, to evaluate the contribution of each predictor variable within the NBCAR-Forest model, variable importance analysis was conducted for each cluster, as presented in Table 3. Simultaneously, the boxplots displayed in Fig. 9 allow for a visualization of the distribution of every variable within the respective clusters.

Table 3 along with Fig. 9 collectively demonstrate the specific meteorological controls categorized by cluster. Cluster 1 assigns highest importance to relative humidity (7.50), followed by wind speed (6.60) and dry days (6.07), with precipitation (4.79) and air temperature (4.52) lower. Fig. 9 illustrates a comparatively elevated humidity, moderate but extensive winds, a significant number of dry days, decreased precipitation, and a narrow temperature interquartile range (IQR), highlighting that moisture availability and wind variability serve as key differentiators. It is consistent with regional findings on ignition suppression under wetter, more humid conditions (Horton *et al.*, 2021; Karurung *et al.*, 2025). Cluster 2 exhibits a wind-led profile: wind speed shows the largest importance (12.53), followed by relative humidity (11.10), air temperature (10.82), and precipitation (10.55), with dry days lowest (5.14). In Fig. 9, wind speed exhibits the greatest range and significant high-end outliers, whereas the other variables display moderate medians and

Table 2: Each cluster's RMSE and MAE values of the NBCAR-forest model

Cluster	RMSE	MAE
1	2.11	1.02
2	5.88	2.92
3	3.69	1.66

Table 3: Variable importance for cluster 1, 2 and 3

Variable	Importance values		
	Cluster 1	Cluster 2	Cluster 3
Precipitation	4.79	10.55	15.84
Relative humidity	7.50	11.10	17.93
Dry days	6.07	5.14	8.74
Wind speed	6.60	12.53	16.15
Air temperature	4.52	10.82	22.35

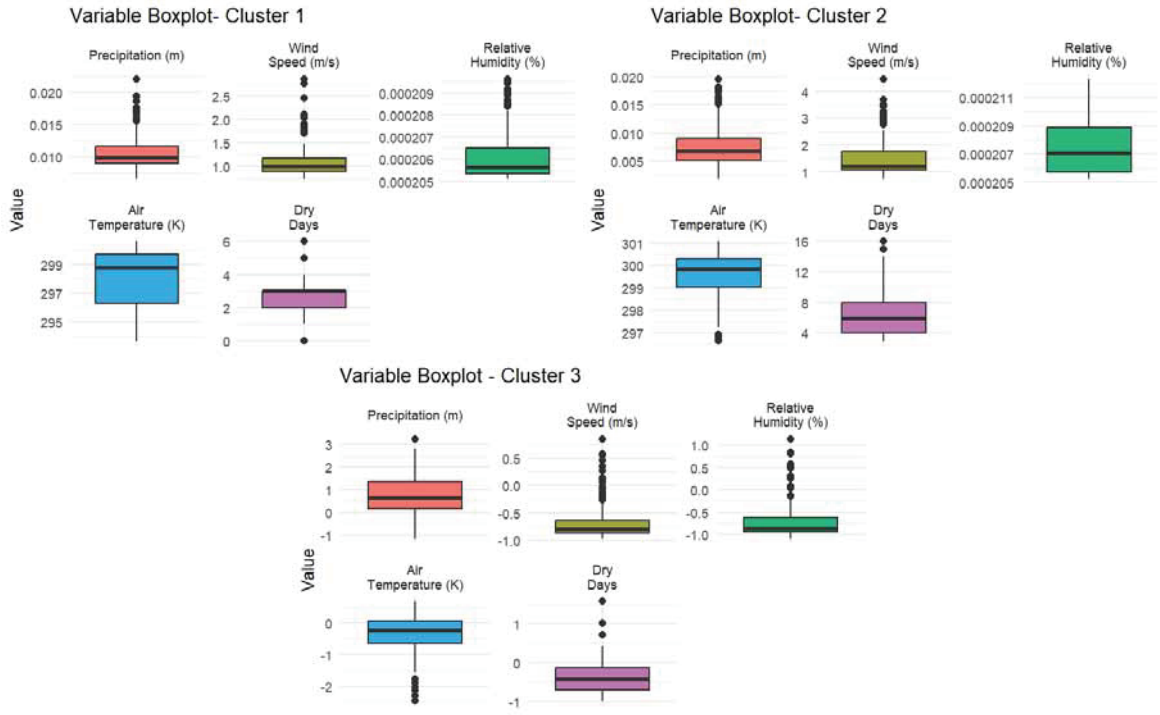

Fig. 9: Multi-panel boxplots for precipitation, wind speed, relative humidity, air temperature, and dry days across the three spatial clusters

variability, consistent with a multi-variable signal that is primarily influenced by wind. Cluster 3 is temperature-dominant: air temperature ranks highest (22.35), then relative humidity (17.93), wind speed (16.15), and precipitation (15.84), with dry days lowest (8.74). As depicted in Fig. 9, there is extensive temperature variability paired with low humidity, which corresponds to the temperature-led management observed in Indonesian peat-forest habitats (Horton *et al*., 2021; Schmidt *et al*., 2024). Cluster-wise summary: Cluster 1 is humidity- and wind-led with the weakest temperature; Cluster 2 is wind-dominated with humidity and temperature secondary; Cluster 3 is temperature-led, followed by humidity, then wind and precipitation. These findings align with regional studies and support targeted early-

warning and mitigation that emphasize humidity management and wind monitoring in wetter zones, wind-driven spread in transitional zones, and heat–dryness thresholds in dry-heat zones.

CONCLUSION

This study compared the performance of the NBCAR-Forest model and the conventional NBCAR model for spatial prediction of the number of hotspots using both simulated and empirical hotspot data from Kalimantan Island. Across all simulation scenarios, NBCAR-Forest consistently produced lower RMSE and MAE values than NBCAR, demonstrating higher predictive accuracy and greater robustness to variations in spatial weight structures (neighbour matrices). The extent of spatial autocorrelation (ρ) emerged as the most significant element influencing model performance; with an increase in ρ, both models faced elevated errors, underscoring the challenges of prediction when strong spatial dependence is present. However, NBCAR-Forest showed minimal performance degradation under different spatial structures, indicating its flexibility. Model performance was also influenced by the variance ratio between predictors and spatial residual effects (ϕ), with the lowest errors occurring when predictor variance substantially exceeded residual variance. In the empirical application to Kalimantan hotspot data for September 2024, NBCAR-Forest achieved relatively low prediction errors (RMSE = 6.54; MAE = 2.60), although slight overestimations persisted in certain regions. Variable importance assessment indicated that relative humidity, air temperature, and wind speed serve as the key predictors, though their effects varied across different spatial clusters. Meteorological controls on the number of hotspots were found to be cluster-specific. In wetter clusters with higher precipitation and stable humidity, meteorological effects were comparatively weak and no single variable dominated. In the transitional, wind-sensitive cluster, wind speed exerted the largest influence, with temperature, humidity, and precipitation contributing at similar magnitudes. In the dry-heat cluster, the strongest signal was observed, led by air temperature and low relative humidity, with wind and rainfall variability refining spatial differences in risk. These patterns suggest that moisture and wind are the primary factors influencing risk in wetter regions, while aerodynamics play a crucial role in transitional zones, and heat–dryness thresholds dictate risk in the driest areas, thereby facilitating cluster-specific early warning and mitigation strategies. The proposed NBCAR-Forest provided superior and adaptive performance for over-dispersed spatial count data. Nonlinear meteorological effects were captured while spatial autocorrelation and regional heterogeneity were explicitly modelled, yielding lower prediction errors than a conventional CAR benchmark and robustness to alternative spatial-weight structures. By integrating feature insights with spatial dynamics, the framework yielded consistent spatial predictions regarding the number of wildfire hotspots that are suitable for evidence-based wildfire risk assessments, proactive warning systems, and strategic mitigation policies. Future studies should build upon NBCAR-Forest by adding further environmental variables (for instance, fuel or vegetation moisture, land-cover/peat metrics) and anthropogenic factors (such as closeness to roads, canals, and settlements). Additionally, it is important to analyze spatio-temporal changes over various seasons and years, and to evaluate its applicability to other fire-prone landscapes. Integrating uncertainty quantification and operational thresholds would further enhance practical relevance.

AUTHOR CONTRIBUTIONS

I. Azis was responsible for conceptualization, methodology, interpreting the results, and writing the original draft. A. Djuraidah conducted the investigation, validation, writing, review, and editing. M.N. Aidi conducted the investigation, visualization, writing, review, and editing. Indahwati handled data curation, formal analysis, writing, review, and editing. A. Sopaheluwakan contributed resources, validation, writing, review, and editing.

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CONFLICT OF INTEREST

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

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
BMKG	Meteorological, Climatological, and Geophysical Agency of Indonesia
CAR	Conditional autoregressive
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	ECMWF re-analysis 5th generation
GRF	Geographical random forest
GWRF	Geographically weighted random forest
ICAR	Intrinsic Conditional Autoregressive
INLA	Integrated nested laplace approximation
INV	Invers distance
IQR	Interquartile range
km	Kilometer
KNN	K Nearest Neighbour
MAE	Mean absolute error
mm	millimeter
MODIS	Moderate resolution imaging spectroradiometer
m/s	Meter per second
NB	Negative binomial
NBCAR	Negative binomial conditional autoregressive
NBCAR-Forest	Negative binomial conditional autoregressive random forest
RF	Random Forest
RMSE	Root mean square error

SAR	Spatial autoregressive
SDGs	Sustainable development goals
SPAR-Forest	Spatial autoregressive random forest
SVM	Support vector machine
TD	Delaunay Triangulation
USA	United States of America
VIF	Variance inflation factor
VIIRS	Visible Infrared Imaging Radiometer Suite

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ORIGINAL RESEARCH PAPER

Bioprospecting and phytochemical profiles of native tropical peatland tree species from the restoration area

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ABSTRACT

BACKGROUND AND OBJECTIVES: Typically, peatland restoration involves the use of native tree species, which are typically advised for their capacity to adapt to the local environment. However, not only ecological, the restoration success also influenced by the economic livelihood of people around the forest. Thus, studies on the exploration of native trees bioprospecting potential is important based on phytochemical properties. The objectives of the study were to explore the bioprospecting potential of trees based on their phytochemical properties, which involved analyzing the phytochemical composition and antioxidant properties of the leaves from four native peatland tree species.

METHODS: The foliage of the peatland tree species was collected from the tropical peat swamp forest located in Central Kalimantan, Indonesia and extracted using ethanol. Phytochemical components, total phenolic, and flavonoid of the leaves were identified and quantified using Liquid chromatography high resolution mass spectrometry. The antioxidant potential was assessed using the 2,2-diphenyl-1-picrylhydrazyl radical scavenging method.

FINDINGS: The characterization shows that the dominant compounds belong to the flavonoid and phenolic group. Among the four species, Dyera polyphylla and Notaphoebe coriacea exhibited the strongest antioxidant activity, with antioxidant activity index values up to 4.77 and 3.20, respectively. In contrast, Rubroshorea balangeran and Metroxylon sago, exhibited strong and moderate antioxidant activity, respectively. The relationship between antioxidant activity and total flavonoid contents showed a notable positive correlation (probability value < 0.05 and correlation coefficient = 0.68). This result is possibly influenced by the presence of bioactive compounds such as coumarin, quercetin, kaempferol and rutin. The bioactive substances identified in this study are encouraging for pharmaceutical advancement. Furthermore, the bioprospecting potential of the compound examined in this study may bolster the sustainability of peatland restoration initiatives both directly and indirectly by safeguarding ecosystem services, carbon stocks, and enhancing the livelihoods of those who depend on forests.

CONCLUSION: This study provides the first report on the secondary metabolites of four native tropical peatland tree species, highlighting their antioxidant and bioprospecting potential. These insights are expected to play a role in enhancing the development of natural products and in the effective restoration of peatland areas.

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INTRODUCTION

Kalimantan island has the second largest peat ecosystems in Indonesia. Peat swamp forests are recognized for their high biodiversity, which provide various resources for human use (Harrison *et al*., 2024). Local communities in the vicinity of these ecosystems depend on both plants and animals to fulfill their everyday requirements. Numerous plants species within peat swamp forest are traditionally utilized for timber, food, medicine, housing material and firewood (Giesen, 2015). Indigenous populations in Kalimantan hold significant traditional wisdom about medicinal flora, using various components of these plants to heal and manage numerous health issues (Kalima *et al*., 2020; Lestariningsih *et al*., 2023). Besides ecosystem services, peat swamp forest also contain huge carbon stock in above or belowground through the plants and soil. Nevertheless, those significant carbon reserves and biodiversity are currently susceptible to disruption. Along with population growth that expanding economic activities, land use change of peat swamp forest have increased for agriculture, plantations, and industrial forestry (Miettinen *et al*., 2016; Kartiwa *et al.,* 2023). The escalation of land conversion has motivated different parties, both governmental and private, to adopt preventative strategies focused on the restoration of peatlands. In 2015, the Government of Indonesia (GoI) established the peat restoration agency to improve peat restoration management in Indonesia. Most forest plant species are commonly recognized for their roles in reforestation and peatland restoration, including *Rubroshorea balangeran*, *Dyera polyphylla* (Adinugroho *et al*., 2024), *Notaphoebe coriaceae* (Bastoni *et al*., 2023), and *Metroxylon sago* (Kadir *et al*., 2022). *Rubroshorea balangeran* is valued as a high-quality timber species. *Dyera polyphylla* latex is widely used in the production of tubes, pipes, varnishes, while its wood serves as raw material for pencils, pulp, paper, and plywood manufacturing (Tata *et al*., 2018). Traditionally, the bark of *Notaphoebe coriaceae* is employed in the production of incense sticks for ceremonial rituals and is also a source material for adhesives (Santosa *et al*., 2016). *Metroxylon sago* is a vital resource for indigenous communities, such as those in Luwu District, South Sulawesi, and the Marind-Anim tribe in Merauke District, Papua. It serves multiple purposes, including food, organic fertilizer, animal feed, fuel, building materials, and cultural activities (Kadir *et al*., 2022). Plants found in forests have important qualities that might aid the pharmaceutical sector. For countless generations, local communities in Kalimantan, Indonesia have incorporated traditional medicine and plant-based healing practices into their cultural heritage (Lestariningsih *et al*., 2023). Various medicinal plants, including grasses, lianas, and woody trees have been utilized as nutraceuticals and traditional medicines. In Kalimantan, the bark of *Rubroshorea balangeran* is used by local communities for enhancing stamina and as a treatment for poisons and dyes (Kissinger *et al*., 2016). The young leaves of *Rubroshorea smithiana* and *Shorea roxburghii* are used to treat diabetes (Lestariningsih *et al*., 2023). The Anak Dalam tribe in Jambi, traditionally uses the latex of *Dyera polyphylla* (locally known as jelutung) to treat wounds, ulcers, and toothaches (Aminah *et al*., 2016). Additionally, the leaves and bark of *Dyera polyphylla* are used in Southern Thailand to relieve fever, inflammation and pain (Subhadhirasakul *et al*., 2003). The bark of *Notaphoebe coriaceae* is employed as a mosquito repellent (Santosa *et al*., 2016). *Metroxylon sago* has been reported to possess medicinal properties for treating various ailments, including skin diseases, chickenpox, wounds, stomach ulcers, flatulence, diarrhea, vomiting, and diabetes (Suciyati *et al*., 2021). A significant number of ethnobotanical and ethnomedicinal studies have documented the application of peat forest plants in traditional healing practices. However, limited research has been conducted on the bioprospecting and potential development of medicinal plant species from tropical peatlands. Bioprospecting is the structured analysis and inquiry into unique phytochemical substances that may have economic significance (Tata *et al*., 2022). The biochemical properties of medicinal raw materials are highly valuable for the pharmaceutical and nutraceutical industries. Therefore, studying the phytochemical composition of native peatland plant species, particularly those utilized in peatland restoration, is essential. Bioprospecting these species has the potential to boost their economic significance and support their sustainable management. The aims of the study are to investigate trees bioprospecting potential based on phytochemical properties by analyzing the composition of phytochemicals and properties of antioxidant from the leaves of four native

peatland tree species. The study was conducted at the restoration area of peat swamp forest in Katingan district, Central Kalimantan province, Indonesia in 2024.

MATERIALS AND METHODS

Research location

The study took place in the restoration area of peatland forest (2° 55′ 45.05″ S – 113° 9′ 14.34″ E) managed by PT. Rimba Makmur Utama, within the peatland hydrological unit (PHU) of Katingan-Mentaya rivers in Central Kalimantan, Indonesia (Fig. 1). According to the Schmidt-Ferguson classification, the climate at the study site is designated as type A (Schmidt and Ferguson, 1951). The average yearly rainfall over the last five years was 3,302 millimeters (mm), while in 2023, the recorded annual precipitation was 2,699 mm. The soil found in the research area is classified as organic, specifically within the Histosols group, as per the soil taxonomy established by the United States Department of Agriculture (USDA) (Soil Survey Staff, 2022). The peat depth ranges from 300 to 400 centimeters (cm).

Four native plant species were selected for analysis, namely: *Dyera polyphylla, Metroxylon sago, Notaphoebe coriacea,* and *Rubroshorea balangeran*. The sample plants were planted between 2018-2019, except for *Metroxylon sago*, which was collected from seedlings in the nursery area (2° 55′ 51.25″ S – 113° 8′ 40.84″ E). Consequently, the ages of the trees were comparable, with the exception of *Metroxylon sago*. The samples were obtained by selecting two individual plants of each species. All the native tree species in this restoration area are results of self propagation with the similar source. The trees were intentionally planted rather than being a product of natural regeneration. Consequently, it was presumed that the variability among the trees was minimal. Leaf samples of trees were collected by cutting the leaves using a scissor. The samples were subsequently stored in envelopes and delivered to the laboratory in Bogor, West Java, for preparation and further

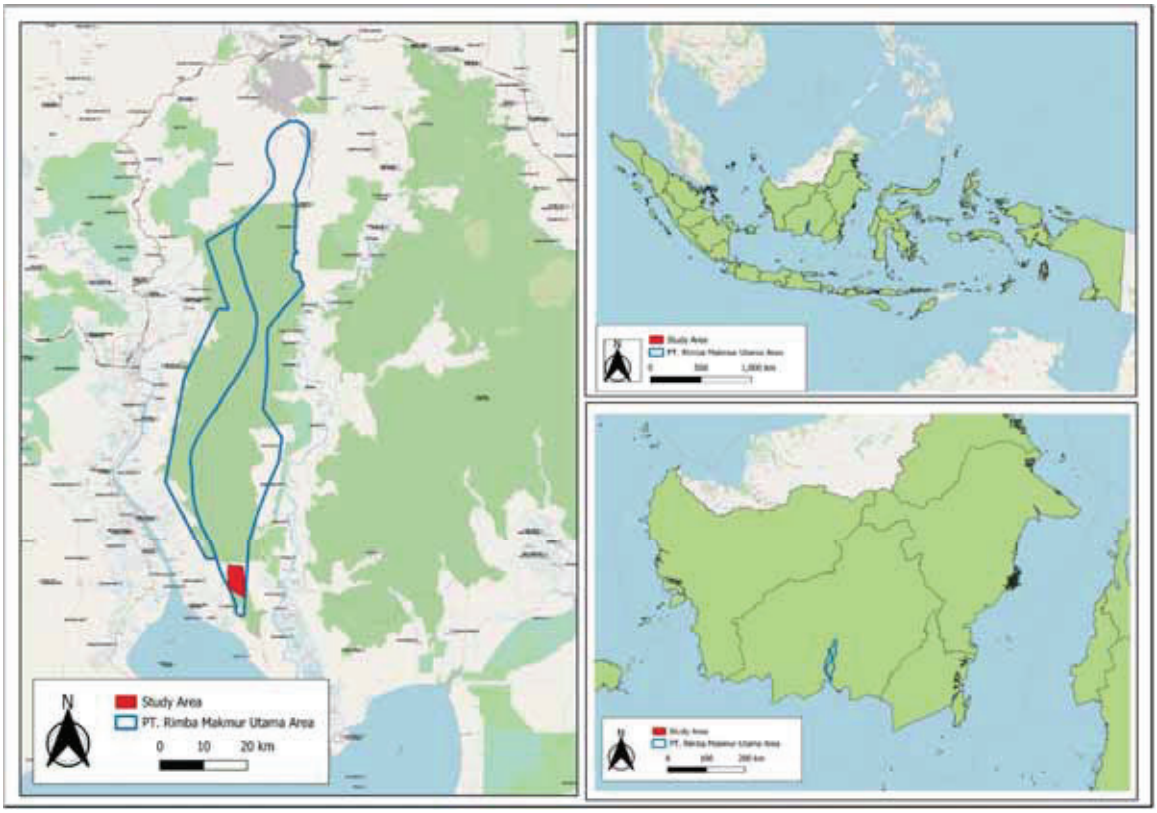


Fig. 1: Geographical location of the study area in Central Kalimantan, Indonesia

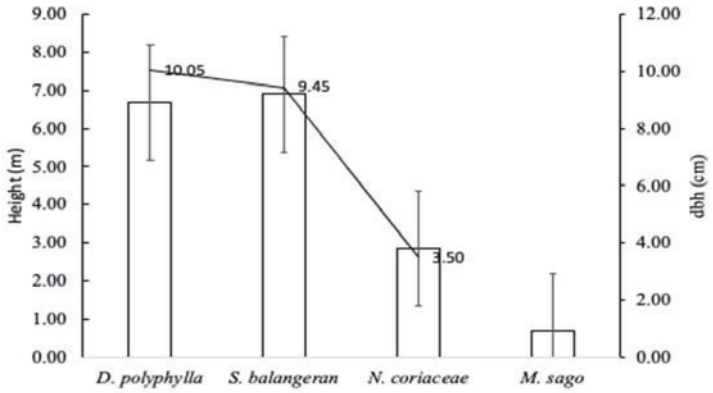


Fig. 2: Height and diameter the breast height (dbh) of tree samples

analysis. Performance data of the sample trees is presented in Fig. 2.

Extraction of plants leaves

Leaf extraction was carried out using the procedure outlined by Fitriani *et al.* (2024). Around 10 grams of dried leaves were used in the process, finely ground leaf samples were macerated using 96 percent (%) ethanol (technical grade solvent). The samples were soaked in 96% ethanol for 24 hours (h). Those process were conducted three to five times. Subsequently, the extracts underwent filtration, and the resulting filtrates were concentrated with a rotary vacuum evaporator to eliminate any residual solvent. The method and time of extraction, solvent and temperature and the time of extraction will affect the yield, structural stability and purity of extracted phytochemicals (Kumar *et al.*, 2022). The extracts obtained were preserved at -20 degrees Celsius (°C) until they were needed again. All extraction procedures were conducted at the natural product laboratory of the National Research and Innovation Agency (BRIN), Cibinong, Indonesia.

Phytochemical characterization

A Thermo Scientific™ Vanquish™ UHPLC Binary Pump that coupled with a thermo scientific™ Q exactive™ hybrid quadrupole-orbitrap™ mass spectrometer was used to analyse the liquid chromatography with high resolution mass spectrometry (LC-HRMS) (Windarsih *et al.*, 2022). All analyses were conducted at the advanced characterization laboratory of BRIN in Yogyakarta, Indonesia. The Total phenolic content (TPC) and total flavonoid content (TFC) were evaluated through the established techniques detailed in priorh (Fathoni *et al.*, 2023; Praptiwi *et al.*, 2020). TPC and TFC was expressed in milligrams of gallic acid equivalents (GAE) and quercetin equivalents (QE) within per kilogram of extract, respectivelly.

Antioxidant activity

The evaluation of antioxidant activity involved calculating the half-maximal (50%) inhibitory concentration (IC_{50}) values through the 2,2-Diphenyl-1-picrylhydrazyl (DPPH) method. While, the inhibitory concentration (IC) was accessed using Eq. 1 (Fathoni *et al.*, 2023):

$$IC\,(\%) = \frac{(Absorbance\ of\ control - Absorbance\ of\ sample)}{(Absorbance\ of\ control)}\ x100 \quad (1)$$

An analysis of linear regression between sample concentration versus IC was conducted to quantified the IC_{50}. The IC_{50} is usually used as drug effectiveness indicator. Lower values of IC_{50} representing higher effycacy of the drug (Meyer *et al.*, 2019).

The Antioxidant Activity Index (AAI) was quantified according to Eq. 2 Scherer and Godoy (2009):

$$AAI = \frac{the\ final\ concentration\ of\ DPPH}{IC50} \quad (2)$$

Statistical data analysis

The difference values of TPC and TFC were analysed using analysis of variance (ANOVA) and Duncan's test for post hoc comparisons using Statistical package for the social sciences (SPSS) 16.0 software. All data

were presented in mean ± standard deviation. While, to assess the relationship among antioxidant activity, TPC, and TFC, Pearson correlation analysis was conducted with significance considered at probability value (p-value) < 0.05.

RESULTS AND DISCUSSION

Phytochemical profile

The characterization revealed that the ethanol extracts of *Dyera polyphylla*, *Metroxylon sago*, *Notaphoebe coriacea*, and *Rubroshorea balangeran* leaves contained diverse secondary metabolites, including alkaloids, flavonoids, phenolics, terpenoids, vitamins, lipids, and other organic compounds (Fig. 3 and Table 1). Flavonoids and phenolics emerged as the primary groups among these, whereas alkaloids, terpenoids, and other minor classes of metabolites played a role in enhancing the overall phytochemical

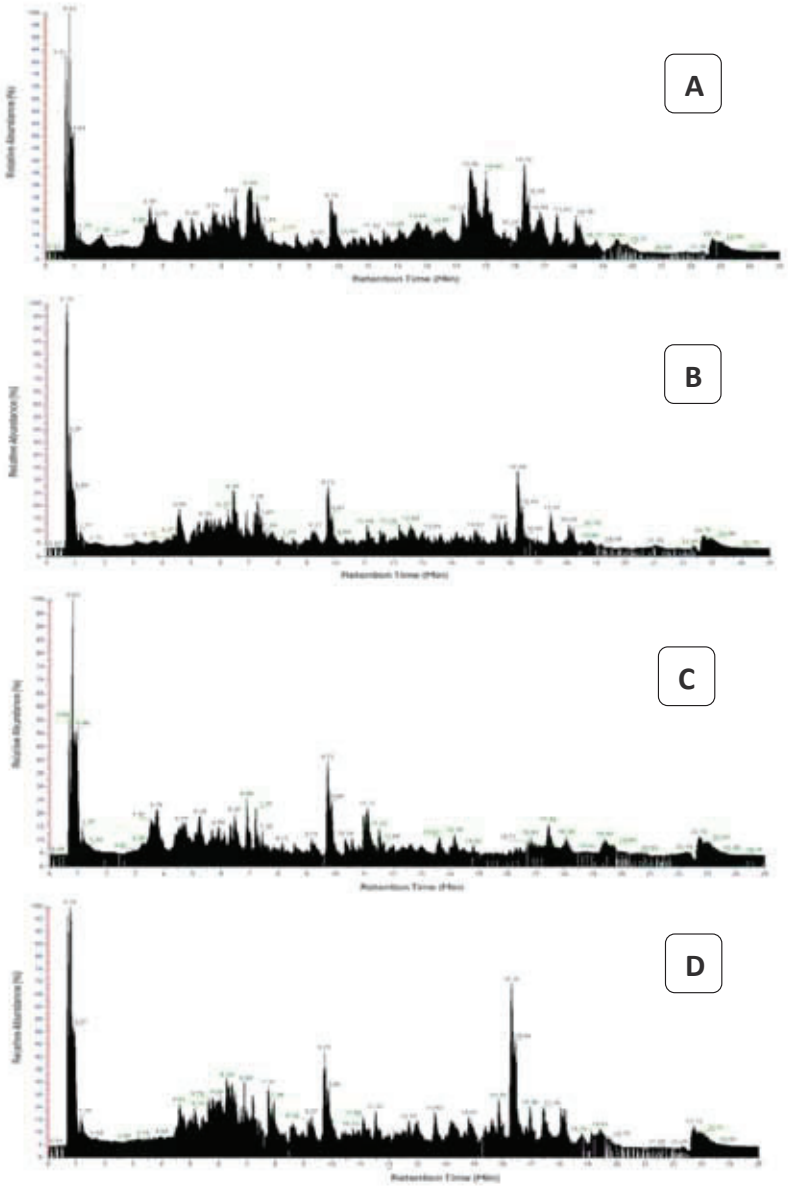


Fig. 3: Total Ion Chromatograms (TIC) ethanol extract of leaves of four peatland tree species. A. *Dyera polyphylla,* B. *Notaphoebe coriacea,* C. *Metroxylon sago,* D. *Rubroshorea balangeran*

Table 1: Yield percentage, TPC, and TFC of ethanol leaf extracts from the four plant species

Parameter	*Dyera polyphylla*	*Metroxylon sago*	*Notaphoebe coriacea*	*Rubroshorea balangeran*
Yield (w/w %)	33.5	23.7	22.8	22.5
TPC (mg GAE/kg extract)	76.00±0.06^{a}	73.14±0.00^{b}	46.21±0.03^{d}	53.71±0.03^{c}
TFC (mg QE/kg extract)	61.00±0.13^{a}	56.83±0.10^{b}	42.54±0.05^{c}	14.66±0.00^{d}

Note: Distinct letters in the data denote a significant difference among the values (p-value ≤ 0.05) as a result of ANOVA analysis.

Table 2: IC_{50} values and AAI of ethanol leaf extracts from four plant species

Parameter	*Dyera polyphylla*	*Metroxylon sago*	*Notaphoebe coriacea*	*Rubroshorea balangeran*	Control+
IC_{50} (µg/mL)	6.69±1.47^{b}	17.71±0.37^{d}	9.67±0.96^{c}	41.19±0.83^{e}	1.23±0.06^{a}
AAI	4.77±1.20^{b}	1.74±0.03^{d}	3.20±0.31^{c}	0.75±0.02^{e}	24.98±1.34^{a}
Antioxidant Category Based on AAI Value	Very strong	Strong	Very strong	Moderate	Very strong

Note: Distinct letters showed significant differences among the values (p-value ≤ 0.05) as a result of ANOVA analysis.

richness and diversity of these species, possibly affecting their bioactivity. The identified flavonoid compounds include tiliroside, quercetin, rutin, kaempferol, cianidanol, myricetin 3-O-beta-D-galactopyranoside, myricitrin, robinin, orientin, hyperoside, coumarin, 2-(3,4-Dihydroxyphenyl)-5,7-dihydroxy-4-oxo-4H-chromen-3-yl-6-O-β-D-xylopyranosyl-β-D-glucopyranoside, afzelechin, and loganetin. Meanwhile, the identified phenolic compounds include picein, abietin, 2,6-dihydroxybenzoic acid, cis-resveratrol, and zingerol.

The TPC and TFC levels of four plant species in the range of 46.21 – 76.00 miligram gallic acid equivalents per kilogram (mg GAE/kg) extract and 14.66 – 61.00 miligram quercetin equivalents per kilogram (mg QE/kg) extract (Table 1). The *Dyera polyphylla* extract has the largest yield, TPC and TFC (33.5, 76.00 ± 0.06 and 61.00 ± 0.13, respectively).

Antioxidant activity

There are several assays to investigate antioxidant acivity, such as ABTS (2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid)), Ferric reducing antioxidant power (FRAP), and oxygen radical absorbance capacity (ORAC), by evaluating different radical mechanisms (Prior *et al.,* 2005; Thaipong *et al.,* 2006). This study focused exclusively on the DPPH method owing to its straightforwardness, ease of execution, sensitivity to stable free radicals, and appropriateness for initial assessment of antioxidant potential (Brand-Williams *et al.,* 1995). Using the DPPH free radical scavenging assay, the ethanol leaf extracts from the four plant species exhibited antioxidant activity ranging from moderate to very strong levels (Table 2). Furthermore, the result of Pearson correlation analysis between antioxidant activity and TFC (correlation coefficient (r) = 0.683, p-value < 0.05) was stronger than TPC (r = 0.329). This outcome may be attributed to the presence of bioactive compounds including coumarin, quercetin, kaempferol and rutin.

Biochemical active compounds and antioxidant activities

The initial assessment of native peatland plant species utilization and preference by the local communities of several villages in the PHU of Mentaya-Katingan rivers in Central Kalimantan showed that some native peatland plant species are usually used as traditional medicine. In light of this, the ongoing study indicates that each of the four native plant species chosen for peatland reforestation possess a variety of beneficial phytochemical compounds. The investigation using LC-HRMS showed that compounds within the four native species primarily belong to the flavonoid and phenolic groups, with flavonoids being more abundant than phenols. In plants, flavonoids and phenolics are recognized as important secondary

metabolites that serve as antioxidants (Ayele *et al*., 2022). In *Shorea* genus, it was reported that about 113 of different compounds are consisted of steroids coumarins, flavonoids, terpenoids, and oligomers (Musa *et al*., 2024). Specifically, the extraction of compounds from the ethyl acetate extract of *Rubroshorea balangeran* stem bark led to the identification of viticanol A, viticanol B, and viticanol G. The quantitative analysis conducted in this study showed significant differences in the concentration of quercetin, rutin, coumarin, and kaempferol varied across species: *Dyera polyphylla* contained 2.56%, 0.51%, 0.33%, and 0.09%, respectively; *Notaphoebe coriacea* 0.36%, 1.22%, 0.16%, and 0.76%; *Rubroshorea balangeran* 1.35%, 0.04%, 0.82%, and 0.76%; and *Metroxylon sago* 1.31%, 0.22%, 2.81%, and 0.53%. In addition, tiliroside (6.4%) and myricetin (3.04%) were exclusively detected in *Rubroshorea balangeran*. These findings demonstrate species-specific phytochemical profiles, with quercetin predominant in *Dyera polyphylla*, rutin in *Notaphoebe coriacea*, coumarin in *Metroxylon sago*, and kaempferol in both *Notaphoebe coriacea* and *Rubroshorea balangeran*. The differences underscore the various potential uses of each species, contingent upon their key bioactive components. These substances are frequently used as active antioxidant agents in both the pharmaceutical and food sectors (Sala *et al*., 2003; Wang *et al*., 2010). In addition, the phytochemical content in the leaf extracts have also been reported to exhibit antioxidant activity, with compounds such as myricetin 3-O-beta-D-galactopyranoside, myricitrin, robinin, cianidanol, ursolic acid, orientin, picein, hyperoside, and afzelechin (Huang *et al*., 2024; Oh *et al*., 2020; Siridechakorn *et al*., 2023; Zhao *et al*., 2023). Due to their antioxidant properties, these compounds are associated with diverse biological activities, including anti-inflammatory, antimicrobial, anticancer, and metabolic disease-related effects, showing promise for applications in food, pharmaceutical, and cosmetic industries. A number of studies have noted that the active compounds within the leaves show bioactivities comparable to those identified in these four peatland tree species, as detailed in (Table 3).

The strong antioxidant activity found in the *Dyera polyphylla* extract is consistent with its high levels of TPC and TFC (Table 1 and 2). Conversely, while *Notaphoebe coriácea* exhibited lower TPC and TFC compared to *Dyera polyphylla* and *Metroxylon sago*, its notable antioxidant potential may be due to the presence of flavonoid compounds known for their powerful antioxidant effects. The ethanol extract of *Rubroshorea balangeran* leaves in this study exhibited moderate AAI. The solvent characteristics and the plant organ employed in extraction play a crucial role in determining antioxidant activity. Previous research showed that methanol extracts from the stem and branches of *Rubroshorea balangeran* exhibited antioxidant activity, with IC_{50} values of 40 micrograms per millilitre (µg/mL) and 50 µg/mL, respectively (Ramadhan *et al*., 2022). In this study, it was discovered that the antioxidant activity of *Dyera polyphylla* extracted with ethanol is more potent compared to that of other Dyera species (such as *Dyera costulata*) extracted with chloroform and n-butanol, as noted bySubhadhirasakul *et al*. (2003). In *Notaphoebe coriácea*, activity of the leaves ethanol extract (IC_{50}=9.67 µg/mL) were stronger than tree bark ethanol extract (IC_{50} 72.36 µg/mL) or chloroform extract (IC_{50} = 54.18 µg/mL) (Putri *et al*., 2021). The findings imply that leaves may possess an increased potential as a source of bioactive compounds. Also, in *Notaphoebe coriácea*, antioxidant activity was found from seed extract, indicated by the occurence activity of catalase, superoxide dismutase, and ascorbate-dependent peroxidase, as well as the ability to chelate ferrous ions and scavenge hydroxyl radicals and hydrogen peroxide (Santosa *et al*., 2016). According to Latayada and Uy (2016), the decoction extract of *Metroxylon sago* leaves showed greater antioxidant activity (IC_{50} = 26.97 µg/mL) than the ethanol extract (IC_{50} = 48.11 µg/mL). However, the ethanol extract of *Metroxylon sago* leaves in this study showed higher antioxidant activity (IC_{50} = 17.71 µg/mL). Despite containing similar components, the latex of *Metroxylon sago* collected from Ron Phibun, Tha Sala, and Phrom Khiri in Thailand exhibited varying antioxidant activity (IC_{50} = 58.83, 88.43, and 18.09 µg/mL, respectively) (Saengsane *et al*., 2018). Antioxidant activity varies based on geographical regions and environmental influences (Musa *et al*., 2024). Furthermore, it has been observed that the peels, flesh, and pith waste of *Metroxylon sago* exhibit antioxidant properties (Wally *et al*., 2024). Furthermore, sago flour demonstrated antioxidant activity comparable to the IC_{50} value of its derived food product. Sago flour is recognized for its antioxidant

Table 3: Biological activities of active compounds in leaf extracts of *Dyera polyphylla, Metroxylon sago, Notaphoebe coriácea, Rubroshorea balangeran*

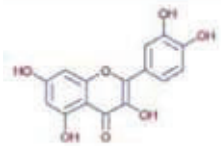
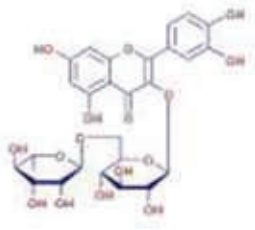
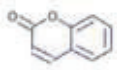
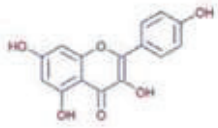
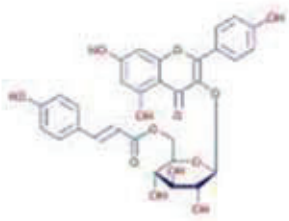
Active metabolite compounds	Structure	Leaf exract of plant species	Biological activities	Sources
Quercetin (C15H10O7)		All four species	Anti-inflammatory, anti-hypertensive, antiviral, anti-bacterial, anti-fibrotic, anticancer, anti-proliferative, anti-atherogenic, anticoagulative, antidiabetic.	Aljadaan *et al.*, 2020; Xiao *et al.*, 2020
Rutin (C27H30O16)		All four species	Anti-inflammatory, antidiabetic, hepatoprotective and cardiovascular effect, antimicrobial, anticarcinogenic, neuroprotective, antithrombotic, anticancer, anti-viral, anticonvulsant, antidepressant, Analgesic, anti-arthritic, antifungal, antihypercholesterolemic, antihypertensive, Antimalarial, antiretroviral, antiulcer, antiasthmatic, antiosteoporotic, anticataract.	Ganeshpurkar and Saluja, 2017; Tobar-Delgado *et al.*, 2023
Coumarin (C9H6O2)		All four species	As CNS-active compounds, antibacterial, anti-inflammatory, anticoagulant, anticancer, antihypertensive, antifungal, antiviral, antitubercular, antiadipogenic, antihyperglycemic, anticonvulsant, neuroprotective, anti-HIV agents, and antitumoural	Bhattarai *et al.*, 2021; Venugopala *et al.*, 2013
Kaempferol (C15H10O6)		All four species	Anti-inflammatory, anticancer, antidiabetic, neuroprotective, hepatoprotective effect, gastroprotective effects, renoprotective effects, cardioprotective activity, anti-microbial, immunomodulatory, role in dental health, role in eye health/disease, anti-arthritis effects, anti-obesity, role in skin health, role of respiratory system, radioprotective effects, anti-thrombosis, anti-depressant, wound healing effects, role in bone disease.	Parveen *et al.*, 2023; Alrumaihi *et al.*, 2024
Tiliroside (C30H26O13)		*Rubroshorea balangeran*	Anti-inflammatory, anti-diabetic, antiglikasi, anticancer, anti-microbial, antifungal, antihyperlipedemic, antiviral, cytotoxic, anti-rheumatism, and hepatoprotective activities.	Dai *et al.*, 2016; Goto *et al.*, 2021; Jia *et al.*, 2019

Table 3: Biological activities of active compounds in leaf extracts of *Dyera polyphylla, Metroxylon sago, Notaphoebe coriácea, Rubroshorea balangeran*

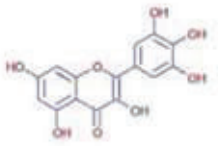
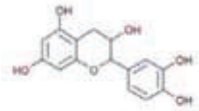
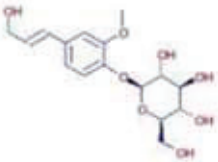
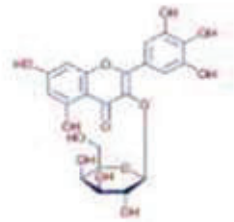
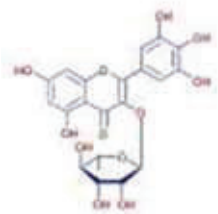
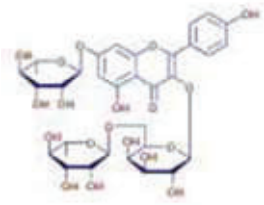
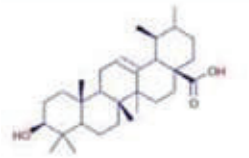
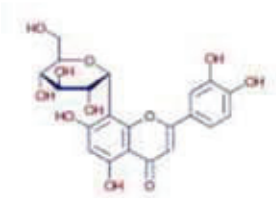
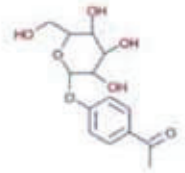
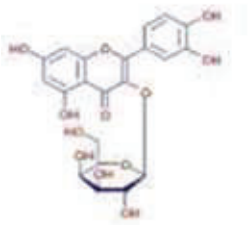
Active metabolite compounds	Structure	Leaf exract of plant species	Biological activities	Sources
Myricetin (C15H10O8)		*Rubroshorea balangeran*	Anti-inflammatory, neuroprotektif, analgesic, anticancer, antidiabetic, antiobesity, cardiovascular protection, osteoporosis protection, hepatoprotective, antimicrobial, immunomodulatory, antihypertensive, and nutraceutical.	Kumar *et al*., 2023; Trivedi *et al*., 2024; Wang *et al*., 2010
Cianidanol (C15H14O6)		*Dyera polyphylla, Metroxylon sago, Notaphoebe coriácea*	Neuroprotective activity, antimicrobial, anticancer, anti-inflammatory, immunomodulating properties.	Belmehdi *et al*., 2023; Rymbai *et al*., 2023
Abietin (C16H22O8)		*Notaphoebe coriácea, Rubroshorea balangeran*	Hypolipidemic activities, precursor of podophyllotoxin, cytotoxic, antifungal, antiviral, insecticidal, neurotoxic, anti-inflammatory, antirheumatic, immunosuppressive, antispasmogenic, and antioxidative.	Yu *et al*., 2017
Myricetin 3-O-beta-D-galactopyranoside (C21H20O13)		*Rubroshorea balangeran*	Antioxidan, antiinflamasi, antiphotoaging, Antinociceptive Activity, antimicrobial	Campos *et al*., 2013
Myricitrin (C21H20O12)		*Rubroshorea balangeran*	Antiinflamasi, anti-fibrotic, antithrombotic,	He *et al*., 2019
Robinin (C33H40O19)		*Notaphoebe coriácea*	Anti-inflammatory, as natural XOD inhibitor for relieving HUA, apoptotic and cytotoxic activity, anti-algal.	Liu *et al*., 2024

Table 3: Biological activities of active compounds in leaf extracts of *Dyera polyphylla, Metroxylon sago, Notaphoebe coriácea, Rubroshorea balangeran*

Active metabolite compounds	Structure	Leaf exract of plant species	Biological activities	Sources
Ursolic acid (C30H48O3)		*Dyera polyphylla*, *Metroxylon sago*, *Rubroshorea balangeran*	Anti-inflammatory, anti-microbial, antitumor, anticancer, antiplatelet aggregation, Antitubercular activity, antifibrotic effect, anti-diabetic agent, antifilarial effect.	Li *et al*., 2022; Luan *et al*., 2022; Xu *et al*., 2022
Orientin (C21H20O11)		*Metroxylon sago*, *Notaphoebe coriácea*	Antiaging, antiviral, antibacterial, anti-inflammation, vasodilatation and cardioprotective, radiation protective, neuroprotective, antidepressant-like, antiadipogenesis, and antinociceptive effects	Lam *et al*., 2016
Picein (C14H18O7)		*Dyera polyphylla*, *Notaphoebe coriácea*, *Rubroshorea balangeran*	Neuroprotectant, antiplatelet activity, antidiabetic	Kesari *et al*., 2020
Hyperoside (C21H20O12)		*Dyera polyphylla*	Anti-obesity, anti-cancer, anti-inflammatory, anti fungal, anti-hepatitis B virus (HBV) effect, anti-inflammatory, anti-depressant, neuroprotective, cardio-protective, anti-diabetic, radio-protective, gastro-protective activities, antibacterial, antiviral, and organ protective effects.	Wang *et al*., 2022; Zhang *et al*., 2023

properties and potential health benefits (Duque *et al*., 2024). The chemical structure, matrix interactions, and digestive processes all play a role in influencing the bioavailability of phytonutrient compounds, while food processing can enhance their stability (Ribas-Agusti *et al.,* 2017; Niaz *et al.,* 2020). Bio-safety is generally associated with potential toxicity and long-term side effects. Some extracts—particularly crude extracts or isolated compounds—exhibit cytotoxic effects against cancer cells with low selectivity toward normal cells, raising safety concerns that could limit their practical application (Ribas-Agusti *et al*., 2017; Niaz *et al*., 2020; Ashidi *et al*., 2010). Specific data data under physiological conditions or extract storage remain limited. In summary, the findings suggest that the four indigenous tree species of peatlands exhibit unique phytochemical and antioxidant characteristics, shaped by both internal and external influences. Intrinsic factors include interactions among bioactive compounds, which can be synergistic or antagonistic, thereby affecting the level of bioactivity (Wagner and Ulrich-Merzenich, 2009). Extrinsic factors include seasonal variation, geographical location, and environmental conditions, which can modulate the content and composition of phytochemicals through the coordination of primary and secondary metabolism (Liebelt *et al*., 2019; Mwamatope *et al*., 2021; Sytiuk *et al*., 2023). Comprehending these regulatory mechanisms is important for maximizing biopharmaceutical quality and ascertaining the ideal time for harvesting (Liebelt *et al*., 2019; Mwamatope *et al*., 2021), while also providing guidance for peatland restoration and bioprospecting strategies. In this context, *Dyera polyphylla* shows the greatest potential for biopharmaceutical applications due to its high quercetin content and strong antioxidant

activity, while *Notaphoebe coriacea*, *Rubroshorea balangeran*, and *Metroxylon sago* are also competitive with established medicinal plants through their unique compounds such as tiliroside, myricetin, and coumarin, which are valuable for pharmaceutical, nutraceutical, and cosmeceutical uses.

Bioprospecting potential of native peatland tree species

Plants that demonstrate antioxidant activity are often employed as alternative therapies for oxidative stress, acknowledged as a crucial factor in the progression of numerous diseases (Kasote *et al*., 2015). An oxidative stress promotes the continuous production of free radicals, leading to extensive tissue damage and contributing to the development of various disorder, including cancer, Alzheimer's, kidney, heart disease, stroke, hypertension, stherosclerosis, cardiomyopathy, asthma, renal failure, arthritis, rheumatism, diabetics, inflammation, and aging (David *et al*., 2016). Acknowledging the vital importance of antioxidants in both preventing and reducing these conditions, there has been considerable work in recent years aimed at identifying effective and non-toxic natural antioxidant substances (Lobo *et al*., 2010). The utilization of natural antioxidants with strong activity and additional health benefits is considered fundamental to bioactivity-based therapies and is regarded as a safer alternative for human health (Li *et al*., 2015). Vaticanol A, B that identified in the ethanol bark extract of *Rubroshorea balangeran*, have shown cytotoxic effects against murine leukemia P-388 cells, with IC_{50} values of 27.0 and 46.4 ppm, respectively (Aryal *et al*., 2019). Additionally, these compounds possess antiprotozoal properties, effectively inhibiting the in vitro growth of *Babesia gibsoni* at concentrations of 25 µg/mL and 50 µg/mL, respectively (Subeki *et al*., 2005). *Notaphoebe coriácea* bark's ethyl acetate extract has revealed bioinsecticidal effects on *Spodoptera exigua* larvae, with a lethal concentration 50% (LC_{50}) value of 0.062% (Humaida *et al*., 2023). Meanwhile, 96% ethanol extract with concentrations of 5-30% of *Metroxylon sago* resulted in antibacterial process versus *Staphylococcus aureus* and *Escherichia coli*, with diameter of inhibition zone at 14-18 and 13-19 mm, respectivelly (Nurlila *et al*., 2021). Furthermore, the inclusion of carvacrol and citral in sago starch-based films led to antimicrobial features, rendering them ideal for edible packaging. These films also exhibited enhanced mechanical properties and a lower water vapor transmission rate, improving their overall functionality for food packaging applications (Dhumal *et al*., 2019). For many years, local communities have made use of traditional medicines, yet the commercialization of herbal and traditional medicine initiates with bioprospecting. In accordance with Regulation number 2 of 2018 issued by Indonesia's Ministry of Environment and Forestry, bioprospecting is defined as the exploration, extraction and screening of natural biological resources for commercial application, including genetic resources, species, biochemicals and their derivatives. This study, which identified phytochemical compounds, TPC, TFC, and antioxidant activity of four peatland tree species, contributes to bioprospecting efforts of traditional medicine derived from the peatland ecosystem of Kalimantan. Identifying bioactive compounds and their antioxidant traits lends scientific evidence to the potential commercial advancement of these four native peatland tree species in the pharmaceutical and nutraceutical markets.

Implications for peat forest restoration

It is essential to utilize tree species from peatlands without logging to support the sustainability of the forest ecosystem (Simangunsong *et al*., 2020). This result may contribute to successful restoration efforts by encouraging the alternative use of non-timber forest products derived from native peat tree species. In addition, without cutting down the trees, it would preserve and increase the carbon stock of the peat swamp forest (Frianto *et al*., 2024). Exploring new alternatives for non-timber forest products (NTFP) is vital for boosting the economic well-being of forest communities and maintaining forest sustainability without resorting to tree logging (Pasaribu *et al*., 2021). Surrounding communities adjacent to the forest might obtain additional incentives by providing tree resources obtained from bioprospecting, all without the extraction of trees. Combining native species with NTFP species is might be one of a promising solution for reaching large scale and financially sustainable forest restoration compare to pure ecological restoration (Gasparinetti *et al*., 2022). NTFP is one of forest management that could be used to promote the low intensity and non-deleterious forest use (Harbi *et al*., 2018). Consequently, this management

approach could serve as a means to reconcile forest conservation and the welfare of forest inhabitants in peat restoration site in Indonesia. Bioprospecting is also a solution for economic restoratif. Phytochemical compounds from some native tree species are take an important role in the ecosystem services and ensures the ecological balance of peat swamp forests. The ecological chemical derived from the biodiversity of Indonesia's forests display a wide variety of ecosystem functions and resilience, being used for traditional medicine, as organic fertilizers, for food production, and in controlling soil erosion (Nugroho *et al.,* 2022). Not only contribute in pharmaceutical development, some of phytochemical compounds are also important to the restoration sustainability. The antibacterial or antifungal compounds of the trees (Table 3) could directly attact the pathogens cell walls and inhibiting protein of the tree diseases (Waszczuk *et al.,* 2022). The significance of this process in the health of forest ecosystems lies in its ability to manage the spread of diseases. The restoration of degraded peatlands including revegetation is challenging because some of peatlands usually experience with fire during the dry season and flooding on the wet season. Based on a systematic review, the average of trees survival for peat swamp forests across Southeast Asia is about 62% (Smith *et al.,* 2022). Data concerning survival rates and growth performance as part of this study is currently in the process of being gathered. In national level, Indonesia has ratified the Nagoya Protocol through Law No. 11 of 2013, thereby strengthening its sovereignty over biological and genetic resources, including traditional knowledge, while underscoring its commitment to sustainable development and equitable access to resources (Masrur *et al.,* 2024). Moreover, Indonesia has launched the Indonesian Biodiversity and Action Plan 2025-2045, which including take immediate action on technical regulation on the benefit sharing framework and intelectual property rights (GOI, 2025). This has the potential to optimize the use of biodiversity and its phytochemical properties obtained through peatland restoration, while ensuring that benefit sharing and property rights are respected among pertinent stakeholders.

CONCLUSION

The native peatland tree species, *Dyera polyphylla, Metroxylon sago, Notaphoebe coriácea,* and *Rubroshorea balangeran* hold dual potential for ecosystem restoration and bioprospecting. This study delivers the initial findings regarding the phytochemical makeup, antioxidant effectiveness, and corresponding biological characteristics of their ethanol leaf extracts. The ethanol leaf extracts derived from *Dyera polyphylla* and *Notaphoebe coriácea* exhibited remarkably high antioxidant activity, positively correlating with flavonoid content—especially quercetin, rutin, coumarin, and kaempferol—recognized for their significant antioxidant properties. Even lower than that of *Dyera polyphylla* and *Notaphoebe coriácea*, *Metroxylon sago* is still included as group of leaves that contain a strong antioxidant activity. *Rubroshorea balangeran* contains richer flavonoid compounds, such as tiliroside and myricetin but showed the lowest or moderate antioxidant activity. Furthermore, these extracts not only possess antioxidant qualities but also include bioactive compounds that are relevant to pharmaceuticals, which supports their promise in the development of future drug development. The revegetation of native species on degraded peatland is very important to restore the peat swamp forest condition. After being planted, those species are prohibited from being logged. These trees should be protected from logging, ensuring that their benefits are sustained over time. By investigating their bioprospecting potential via non-timber applications, like leaf extracts, communities can achieve economic and health advantages while still upholding conservation goals. Thus, studies on the plant parts bioprospection are important to increase the sustainable utilization of peat swamp forests. This dual approach not only supports the advancement of natural product-based industries but also strengthens sustainable peatland management and biodiversity conservation. Furthermore, the numerous benefits provided by peat swamp forests would enhance the community's commitment to preserving these vital ecosystems. Thus, the cultivation and reforestation of these native peatland species offer a sustainable strategy to advance bioprospecting initiatives while simultaneously promoting peatland ecosystem restoration. Ultimately, these results illustrate that local peatland trees constitute a largely unexploited source of bioactive compounds with substantial scientific, economic, and ecological value. Their integration into nature-based solution strategies can simultaneously promote ecosystem restoration,

improve sustainable livelihoods, and promote the long-term conservation of tropical peat swamp forests. Future studies ought to further investigate the chemical variety, pharmacological effects, and sustainable uses of these species to enhance their role in conservation and innovation. In the future, the pharmaceutical sector could continue to rely on the sustainable cultivation and harvesting practices for raw materials and bioactive ingredients. Forest restoration and the domestication of plant species support initiatives aimed at securing a sustainable source of raw materials for the development and commercialization of traditional medicines. Simultaneously, the revegetation of native peatland tree species enhances their ecological and economic value, contributing to global peatland restoration initiatives. These findings not only reinforce the pharmacological significance of indigenous peatland species but also correspond with worldwide initiatives in sustainable land management and economies based on biodiversity. More future studies are needed to increase the sustainable benefit of ecosystem services of tropical peat swamp forests as a potential of nature based solution.

AUTHOR CONTRIBUTIONS

D. Handayani, the first author has contributed in writing original draft, writing review and editing, methodology, investigation, validation, formal analysis, and data curation. A. Fathoni performed in conceptualization, investigation, methodology, writing original draft, review, editing, data curation, validation, and data analysis. H.L Tata has contributed in conceptualization, writing original draft, validation, review and editing, project administration, methodology, investigation, resources, funding acquisition, data curation and analysis. R. Ura' has contributed in writing original draft, writing review, editing, investigation, analysis, and data curation. S. Sundari has contributed in writing original draft, editing, methodology, investigation, formal analysis, validation, and data curation. F. Azwar has contributed in writing original draft, graphical abstract, methodology, and investigation. Bastoni has contributed in writing review and editing, methodology, investigation, and validation. N. Wakhid, the corresponding author has contributed in writing review and editing, methodology, investigation, analysis, and validation. H. Siahaan has contributed in writing review, editing, methodology, and investigation. B.T Premono has contributed in writing review and editing, methodology, validation and investigation. Nuralamin has contributed in writing, review and editing, validation. Purwanto has contributed in review, editing, and validation. D.P Astuti has contributed in writing review and editing, validation, and project administration. T. Darusman has contributed in writing review and editing, validation, and resources.

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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.

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ABBREVIATIONS

%	Percent
°C	Degrees Celsius
µg/mL	Micrograms/millilitre
AAI	Antioxidant Activity Index
ABTS	3-ethyl-benzothiazoline-6-sulfonic acid
ANOVA	Analysis of variance
BRIN	National Research and Innovation Agency
cm	Centimeters
DPPH	Diphenyl picrylhydrazyl
E	East
e.g.	Exempli gratia (for example)
ELSA	Electronic service of science
FRAP	Ferric reducing antioxidant power
g	Gram
GAE	Gallic acid equivalents
GoI	Government of Indonesia
h	hours
IC	Inhibitory concentration
IC_{50}	half-maximal Inhibitory concentration
ID	Identification
kg	Kilogram
LC- HRMS	Liquid chromatography-High resolution mass spectrometry
LC_{50}	Lethal concentration 50%
mg GAE/kg	Miligram gallic acid equivalents per kilogram
mg QE/kg	Miligram quercetin equivalents per kilogram
mm	Milimeters
mol	Mole
NTFP	Non-timber forest products
ORAC	Oxygen radical absorption capacity
PHU	Peatland hydrological unit
ppm	Parts per million
p-value	Probability value
Q Exactive	Quadrupole exative
QE	Quercetin equivalents
r	Correlation coefficient
RIIM	Research and Innovation for an Advancing Indonesia
Rt	Retention time
S	South
SPSS	Statistical package for the social sciences
TFC	Total flavonoid content
TIC	Total Ion Chromatograms
TM	Trademark
TPC	Total phenolic content
UHPLC	Ultra-High Performance Liquid Chromatography
USDA	United States Department of Agriculture
w	Weight

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CASE STUDY

Potential impact of urbanization on heavy metals accumulation in surface soils of rapidly urbanizing cities

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ABSTRACT

BACKGROUND AND OBJECTIVES: Rapid urbanization significantly alters soil quality by influencing its chemical properties and accelerating the accumulation of toxic metals. Moreover, despite the extensive studies on vehicular emissions and their impact on metals like lead, zinc, and copper, limited studies have comprehensively examined how various human activities interact to shape heavy metal contamination across different urban gradients. This study addresses this critical knowledge gap by integrating high-resolution spatial analysis, multivariate statistical modeling, and ecological risk assessment to unravel the combined effects of transportation density, construction intensity, and industrial expansion on soil contamination.

METHODS: Ninety geo-referenced topsoil samples were collected from residential, industrial, recreational, and roadside areas. Ten priority toxic metals, including cadmium, lead, chromium, copper, zinc, nickel, cobalt, manganese, arsenic, and mercury, were analyzed using high-resolution mass spectrometry. To assess concentration patterns and identify possible sources of pollution, spatial interpolation and multivariate statistical analyses were employed. Additionally, human health and ecological risk assessments were conducted to evaluate potential hazards associated with soil contamination.

FINDINGS: Concentrations of metals revealed notable spatial differences across diverse urban land-use classifications. High-resolution inductively coupled plasma mass spectrometry detected high lead concentrations reaching 375 milligrams per kilogram and zinc up to 492.7 milligrams per kilogram. Cadmium concentrations, although lower in absolute terms, peaked at 2.1 milligrams per kilogram but contributed disproportionately to ecological risks. Mercury concentrations were relatively low, peaking at 0.9 milligrams per kilogram, whereas chromium, copper, and nickel levels were recorded at 142.6, 160.3, and 89.5 milligrams per kilogram, respectively, suggesting possible contributions from multiple sources beyond just vehicle emissions. Principal component analysis explained 78.3 percent of total variability and revealed three dominant components, with the first (34.7 percent) strongly influenced by lead, zinc, and copper, confirming traffic-related inputs.

CONCLUSION: The study underscores the notable effect of fast-paced urban development on soil contamination and delivers crucial information regarding the spatial distribution, sources, and risks associated with toxic metals in urban soils. These findings are essential for guiding land-use planning, environmental management, and the development of targeted mitigation strategies in rapidly expanding cities.

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INTRODUCTION

Urban soil pollution, particularly by heavy metals, has become an increasingly critical concern in the context of rapid urbanization, industrialization, and transportation activities. As cities progress and expand, the requirement for infrastructure and advancement escalates, causing a surge in emissions of pollutants, particularly heavy metals (Manzueta *et al.*, 2024; Idroes *et al.,* 2024). These metals, such as cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), zinc (Zn), nickel (Ni), cobalt (Co), manganese (Mn), arsenic (As), and mercury (Hg), have widespread environmental and human health implications due to their persistence and bioaccumulation in the ecosystem (Ali *et al.*, 2019; Mitra *et al.*, 2022; Hawrami and Baset, 2024). The quick development of metropolitan zones is commonly associated with poor waste management practices and limited enforcement of regulations, which intensifies the buildup of heavy metals in urban soils. These soils, being sinks for pollutants, absorb and store harmful substances, posing long-term risks to human health, especially in densely populated areas (Phaenark *et al.*, 2024). For instance, in the study conducted by Rana *et al.* (2024) in Bangladesh, it was observed that street dust in industrial areas exhibited significantly elevated concentrations of heavy metals, such as Mn at 444.35 milligrams per kilogram (mg/kg), Zn at 299.25 mg/kg, Cr at 238.31 mg/kg, and Pb at 54.22 mg/kg. The pollution load index (PLI) has been recorded at 2.45, signifying elevated contamination levels. Health risk assessments revealed heightened non-carcinogenic risks for children and possible cancer risks due to Cr exposure via inhalation, with values ranging from 1.13×10^{-4} to 5.96×10^{-4}. This highlights the serious health consequences of heavy metal buildup in urban areas. Heavy metals are unique in that they do not degrade over time and persist in the environment, making them a long-term threat to both ecological systems and human populations (Das *et al.*, 2023). These metals are toxic at even low concentrations and can accumulate in the food chain, leading to adverse effects on plants, animals, and humans. In urban settings, heavy metals build up in the soil, where they may be taken up by plants, consumed by animals, or inhaled by humans (Perković *et al.*, 2022). Long-term exposure to these contaminants can lead to various health problems, including developmental issues in children, neurological disorders, and increased cancer risk (Jaishankar *et al.*, 2014). The persistence of heavy metals in the environment, combined with their ability to bioaccumulate, makes it crucial to assess and mitigate the risks they pose to both the environment and public health, especially in urban settings where pollution levels are often higher. Much of the research has been directed towards heavy metal pollution in industrialized cities; however, the rising urban sprawl in developing nations brings forth a unique set of challenges. In these rapidly expanding urban centers, regulatory infrastructure may not yet be fully developed, leaving many areas vulnerable to unchecked pollution (Peter and Yang, 2019). Often, these cities are deficient in the monitoring and enforcement frameworks required to manage the emission of heavy metals and various pollutants, which makes them especially vulnerable to environmental deterioration. The absence of robust environmental regulations means that contamination levels are often underreported, and the full extent of pollution is unknown. This creates a significant gap in knowledge, particularly in fast-growing cities where the risk of contamination is high. Understanding the distribution, sources, and impacts of heavy metal pollution in these cities is crucial for implementing effective policies and interventions that can protect both human health and the environment. Urban soils function as a sink for contaminants originating from multiple human activities sources, including vehicle exhaust, industrial effluents, atmospheric deposition, and construction activities (Yang *et al.*, 2011). These sources continuously release heavy metals into the environment, where they are deposited on the soil surface. The emissions produced by vehicles, especially those that are older and utilize fuels containing higher levels of metals, significantly contribute to the presence of metals like Pb, Zn, and Cu in urban soils (Kuklová *et al.*, 2022). Industrial activities, including the burning of fossil fuels, waste incineration, and manufacturing processes, are also major contributors. Furthermore, atmospheric deposition, where pollutants are transported by wind and settled on the ground, intensifies contamination levels (Amodio *et al.*, 2014). The combination of these diverse sources makes urban soils a key medium for monitoring environmental pollution. Comprehending the accumulation of pollutants in urban soils is vital for creating effective strategies to manage contamination and reduce its consequences

(Luo *et al.*, 2024). The topsoil layer of urban soils tends to accumulate pollutants more readily than deeper soil layers, making it a critical medium for monitoring environmental quality (Yang *et al.*, 2024). This is particularly true for heavy metals, which are often immobile in soil and remain concentrated in the upper layers. Given that the topsoil is the primary area for various human activities such as agriculture, construction, and recreation, it represents the most probable point of human interaction (Sánchez-Castro *et al.*, 2023). Through the identification of contamination patterns in urban soils, researchers can locate areas with significant exposure and evaluate the corresponding risks to both human health and ecosystems (Proshad *et al.*, 2024). This information is essential for guiding urban planning and policy decisions, such as zoning, land use, and public health interventions. Comprehending how pollutants are spatially distributed in urban soils enables focused actions that can minimize exposure, especially in sensitive locations like residential neighborhoods, schools, and playgrounds. Despite the swift expansion of cities around the globe increasing human-induced pressures on urban ecosystems, resulting in significant heavy metal pollution in soils, the overall scope, distribution, and ecological hazards of these contaminants—especially in developing urban areas—are still not well comprehended. Moreover, despite increasing concerns about urban soil contamination, previous studies in Central Asia and globally have largely focused on isolated sources, such as vehicular emissions or industrial discharges, without integrating multiple anthropogenic drivers or assessing their combined ecological risks across urban gradients. This study bridges that gap by providing the first comprehensive assessment that integrates high-resolution spatial analysis, multivariate statistical modeling, and ecological risk evaluation to examine how diverse urban activities collectively influence heavy metal contamination across residential, industrial, recreational, and roadside soils in Astana, Kazakhstan. The aim of this study was to evaluate the impact of rapid urbanization on heavy metal contamination in surface soils of Astana, Kazakhstan. It focuses on assessing the concentrations, spatial distribution, and potential sources of ten priority heavy metals. An integrated multi-method strategy was utilized, incorporating geostatistical analysis, receptor modeling, along with evaluations of human and ecological risks. This study addresses this critical gap by providing detailed spatial and risk-based insights into heavy metal contamination across diverse land-use zones with a case of Astana, Kazakhstan, conducted in 2024.

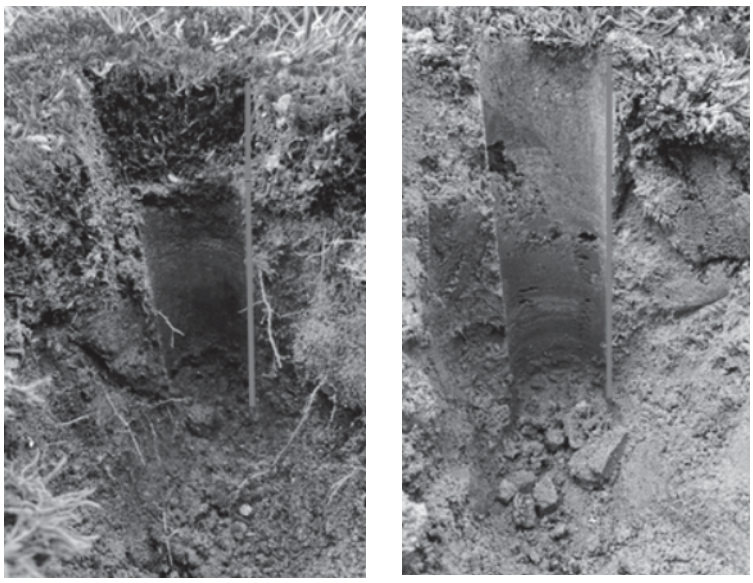
MATERIALS AND METHODS

Soil sampling and site selection

A total of 90 surface soil samples with depth: 0–20 centimeters (cm) were collected during the dry season to minimize moisture-related variability (Fig. 1). The study area was systematically stratified into four predominant urban land-use categories: residential (n = 25), industrial (n = 25), recreational (n = 20), and roadside (n = 20). Sampling sites were previously identified utilizing a randomized grid overlay method in a geographic information system (GIS) to guarantee representative coverage. At each site, three subsamples were collected within a 1-meter radius and homogenized to form one composite sample. All sampling points were geo-referenced using a handheld global positioning system (GPS) unit (Garmin GPSMAP 64s) with a positional accuracy of ±3 meters (m) to enable precise spatial analysis and geostatistical modeling. Baseline concentrations of metals in the soil were determined using surface samples (0–20 cm) collected from peri-urban regions of Astana that are minimally influenced by industrial, traffic, or other human activities. Reference sites were selected to match the soil texture, parent material, and geomorphology of the urban study locations. At each site, three subsamples within a 1-meter radius were homogenized to form a composite sample. The average concentrations derived from these reference soils were employed to determine local geochemical background values, which represent the natural features of the region.

Sample preparation and heavy metal analysis

The soil samples underwent air drying at ambient laboratory conditions, maintaining a temperature of 20 to 25 degrees Celsius (°C) for 72 hours. Subsequently, they were gently disaggregated and passed through a 2 millimeters (mm) polyethylene mesh to remove gravel and organic debris (Fig. 1). For metal analysis, 0.5 grams (g) of each dried soil sample was digested using aqua regia (hydrochloric acid (HCl): nitric acid (HNO_3) = 3:1 volume-to-volume ratio) following the United States Environmental Protection



(a) (b)

Fig. 1: Soil sampling at different locations (a) roadside (b) recreational

Agency (USEPA) Method 3051A (Bettinelli *et al.*, 2000) in a microwave-assisted digestion system (CEM Mars 6, USA). The digests were filtered, diluted to 50 milliliters (mL) with ultrapure water with resistivity >18.2 megaohm-centimeter (MΩ·cm), and analyzed using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7900). The target elements included Cd, Pb, Cr, Cu, Zn, Ni, Co, Mn, As, and Hg. In order to maintain data quality and reliability, each analytical batch included certified reference materials (NIST SRM 2711a), method blanks, and duplicate samples. Recovery rates ranged from 91 percent (%) to 106%, and relative standard deviations (RSDs) for replicate analyses were maintained below 5%. Soil samples were analyzed for key physicochemical properties known to influence metal mobility, including pH, organic matter (OM), and cation exchange capacity (CEC). Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter, revealing a slightly alkaline to neutral range (7.2–7.8), which can reduce the solubility of many metals such as Pb and Cu. Using the Walkley–Black method, the organic matter content was assessed to be between 2.1% and 3.8%, which reflects a moderate potential for complexation capable of immobilizing metals including Cd and Zn. CEC, measured by the ammonium acetate technique, fluctuated between 12–24 cmol/kg, reflecting the soil's ability to hold cations and regulate metal availability. These parameters collectively offer insight into metal mobility and bioavailability in Astana's urban soils.

Spatial distribution and geostatistical analysis

The spatial variability of heavy metal concentrations was analyzed using ArcGIS Pro 3.2 (ESRI, USA). Ordinary kriging, a robust geostatistical interpolation method, was applied to develop spatial distribution maps for each metal. Data normality was assessed prior to interpolation and improved using log transformation as needed. Semivariograms were modeled and cross-validated using root mean square error (RMSE) and mean standardized error metrics. To evaluate the presence of spatial autocorrelation, the Global Moran's I statistic was computed, revealing whether the distribution patterns of heavy metals were clustered, dispersed, or random. Moran's I and semivariogram analysis were employed to test the spatial autocorrelation of metal concentrations, assessing the level of clustering or dispersion in the study area. Significant positive Moran's I values ($p < 0.05$) confirmed that metal concentrations were not randomly distributed but exhibited spatial dependence, justifying the use of geostatistical interpolation methods such as ordinary

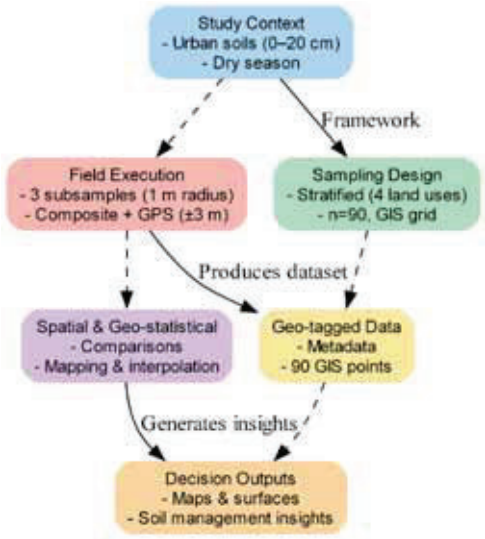


Fig. 2: Soil sampling conceptual framework

kriging. An exponential model was employed to fit semivariogram models, optimizing nugget, sill, and range parameters for each metal, followed by cross-validation to determine prediction accuracy. High correlation coefficients ($r^2 > 0.85$) and low root mean square errors (RMSE) indicated robust interpolation, supporting reliable spatial mapping of contamination hotspots and informing targeted risk management.

Multivariate statistical analysis

Potential contamination sources and underlying data structures were identified using principal component analysis (PCA) with varimax rotation and hierarchical cluster analysis (HCA) based on Ward's method with squared Euclidean distance. The suitability of the data for PCA was verified using the Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of sphericity. To quantify the contribution of potential pollution sources, positive matrix factorization (PMF 5.0), developed by the US EPA, was employed. The model underwent various iterations with different factor counts, and the most interpretable solution was selected based on minimized Q values and residuals. The calculation of uncertainty inputs was based on both instrumental errors and the detection limits of the method. Fig. 2 presents the conceptual framework of the study, outlining the progression from study context and sampling design through field execution and data generation to spatial analysis and decision-oriented outputs.

Human health risk assessment

The human health risk was assessed for two sensitive population groups; children (1–6 years) and adults (30–60 years); following US EPA guidelines of risk assessment guidance for superfund (RAGS), Part A). Exposure pathways included ingestion, inhalation of soil particles, and dermal contact. For each pathway, the average daily intake (ADI) was calculated by utilizing standard equations that account for exposure frequency, duration, and body weight. Non-carcinogenic risk assessment was conducted through the hazard quotient (HQ) and hazard index (HI), whereas the evaluation of carcinogenic risk (CR) relied on element-specific cancer slope factors (CSFs). An HI >1 indicates potential for adverse health effects, while a CR range of 10^{-6} to 10^{-4} was considered acceptable.

Ecological risk assessment

Two complementary indices were utilized to fully evaluate the ecological risks related to heavy metal contamination in urban soils. The first index, the potential ecological risk index (PERI), integrates three key parameters: the measured concentration of each metal, its respective toxicity response coefficient, and the natural background concentration. Initially, the ecological risk factor for each element is identified, and subsequently, the cumulative risk for all metals is calculated to produce the overall PERI value. This approach enables the classification of ecological risk

levels as low, moderate, considerable, or very high. In this study, Cd and Hg were the most significant contributors to ecological risk, particularly in industrial and roadside zones, with individual risk factors (Er_i) exceeding 160 and 120, respectively. These values identified the areas as experiencing significant to high ecological risk, highlighting the impact of industrial discharge and vehicular emissions. The PERI framework proved effective in identifying pollutant-specific threats and in prioritizing zones requiring urgent ecological management, using Eqs. 1 and 2 (Chen *et al.*, 2019; Custodio *et al.*, 2021):

$$Er_i = T_i \times \left(\frac{C_i}{B_i} \right) \quad (1)$$

$$PERI = \sum Er_i \quad (2)$$

Where, Er_i = Ecological risk factor for the individual metal i, T_i = Toxic response factor for metal i (e.g., Cd = 30, Hg = 40, As = 10, etc.), C_i = Measured concentration of metal i in the soil (mg/kg), B_i = Background concentration of metal i in the soil (mg/kg), usually derived from regional geochemical baselines.

Two complementary indices were adopted to fully evaluate the ecological risks tied to heavy metal contamination in urban soils. The primary index, referred to as the PERI, incorporates three vital parameters: the concentration of each metal that has been measured, its associated toxicity response coefficient, and the natural background concentration. The ecological risk factor for each element is first determined, and then the cumulative risk across all metals is computed to yield the overall PERI value. This approach enables the classification of ecological risk levels as low, moderate, considerable, or very high. In this study, Cd and Hg were the most significant contributors to ecological risk, particularly in industrial and roadside zones, with Er_i exceeding 160 and 120, respectively. These values designated the zones as facing significant to high ecological risk, underscoring the impact of industrial discharge and vehicular emissions. The PERI framework proved effective in identifying pollutant-specific threats and in prioritizing zones requiring urgent ecological management, using Eq. 3 (Custodio *et al.*, 2021):

$$I_{geo} = log_2 \left(\frac{C_n}{1.5 \times B_n} \right) \quad (3)$$

Where, Igeo = Geoaccumulation index for a given heavy metal, C_n = measured concentration of the metal in the soil (mg/kg), B_n = Geochemical background concentration of the same metal (mg/kg), 1.5 = Constant factor that accounts for potential variations in background data due to lithogenic (natural) variability, log_2 = Base-2 logarithm used to scale the index.

Soil microbial activity assessment

In order to better comprehend the ecological consequences of heavy metal contamination, soil microbial activity was analyzed in a group of 36 representative samples collected from residential, industrial, recreational, and roadside areas. Microbial biomass carbon (MBC) was determined using the chloroform fumigation–extraction method, while basal soil respiration (BSR) was measured through carbon dioxide (CO_2) evolution over a 7-day incubation period at 25 ± 1 °C. Furthermore, the quantification of dehydrogenase enzyme activity (DHA) was conducted colorimetrically through the reduction of triphenyltetrazolium chloride (TTC), since DHA is a sensitive indicator of microbial metabolic potential. These microbial endpoints were selected because they provide early signals of ecosystem stress caused by heavy metal contamination. To ensure quality control, measurements were conducted in triplicate, and all microbial parameters were standardized to the dry weight of the soil for comparative analysis among various land-use types.

RESULTS AND DISCUSSION

The background soil concentrations in peri-urban areas of Astana indicate generally low levels of metals, reflecting minimal anthropogenic influence and natural geochemical conditions. Pb, Zn, Cu, and Ni show slightly higher values compared to other metals but remain well below urban contamination thresholds, consistent with natural mineralization in the region. Cd, As, and Hg demonstrate extremely low levels, indicating minimal contribution from industrial, vehicular, or agricultural activities. Mn and Cr are relatively higher but display low variability, characteristic of the local soil parent material (Fig. 3).

Descriptive statistics of heavy metal concentrations

The concentrations of heavy metals in the urban soils of Astana reveal both notable similarities and

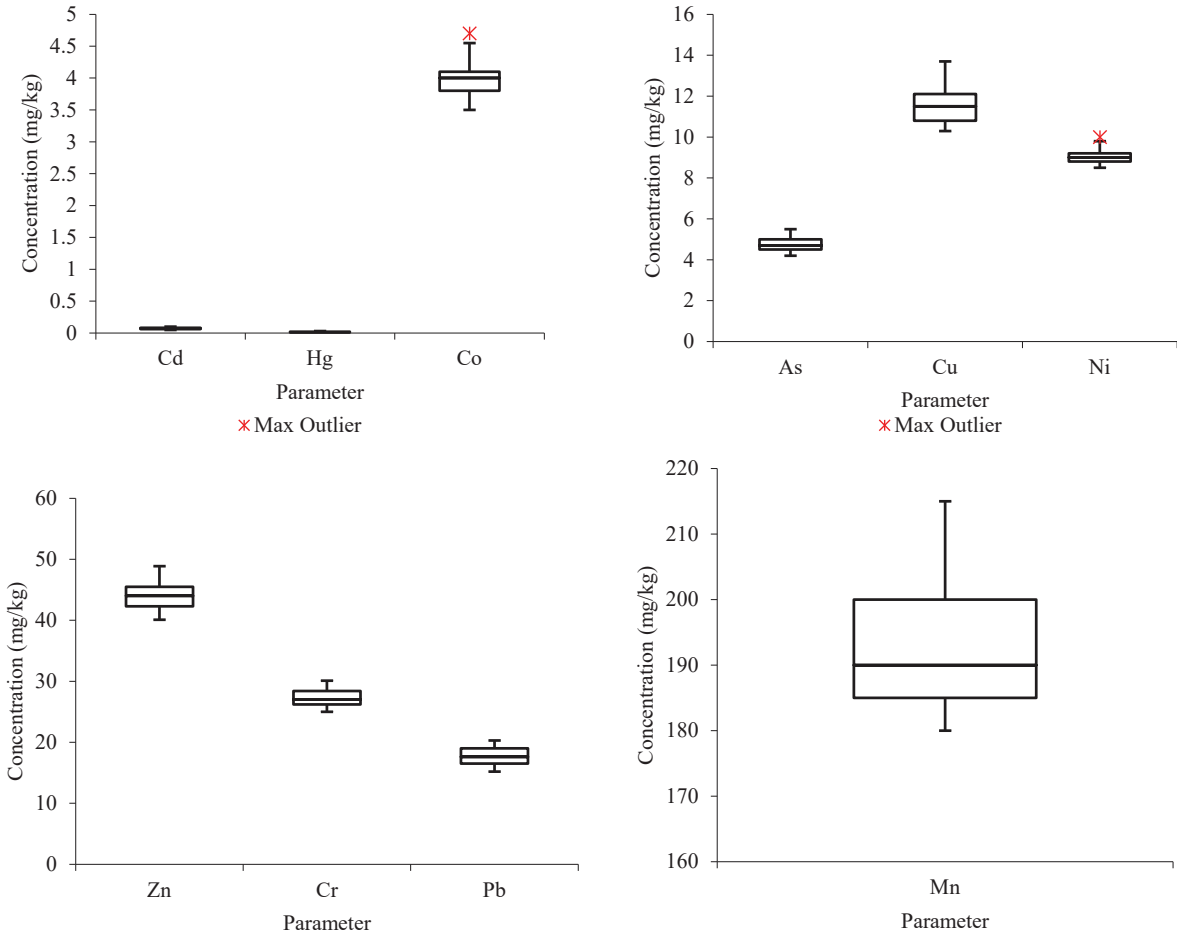


Fig. 3: Boxplots showing the distribution of baseline soil metal concentrations

differences in comparison to other fast-developing cities with comparable climatic conditions and development trajectories. The elevated concentrations of Pb, Cd, and Hg observed in Astana, with maximum values reaching 375 mg/kg, 2.1 mg/kg, and 0.9 mg/kg, respectively, exceed international soil quality guidelines and indicate strong anthropogenic influence, particularly near roadside and industrial zones. This pattern is consistent with studies from Wuhan, China, where accelerated industrialization and congested transportation networks have led to pronounced spatial heterogeneity of Pb and Cd. The use of geographically weighted regression (GWR) models has uncovered strong links between heavy metal hotspots and anthropogenic drivers (Sun *et al.*, 2025). However, unlike Wuhan, where Cu and cadmium concentrations are more influenced by natural geochemical backgrounds, Astana exhibits consistently elevated Cu levels (mean 74.5 mg/kg) and significant cadmium variability (%CV 67.1%), pointing toward localized contamination from industrial emissions, electronic waste disposal, and traffic-derived particulates. Comparisons with Nanchang, China, further underscore Astana's distinctive contamination profile. In Nanchang, soil Pb, Cd, and Cr levels decrease markedly with increasing urbanization intensity due to enhanced sequestration by glomalin-related soil proteins (GRSP), which exhibit strong adsorption capacities for heavy metals (Tu *et al.*, 2025). Conversely, the consistently elevated levels of Pb and Cd in Astana, even in newer urban districts, indicate a lack of effective natural attenuation mechanisms. This likely reflects lower organic matter content and diminished GRSP-mediated

sequestration under semi-arid climatic conditions. Similarly, findings from Łódź, Poland, a post-industrial city with a comparable continental climate, reveal high Zn, Pb, and Cu enrichment near industrial and high-traffic zones, where approximately one-third of urban soils are highly contaminated (Wieczorek *et al.*, 2020). Yet, Astana shows broader spatial variability, with coefficients of variation exceeding 60% for several metals, reflecting both localized hotspots and a less uniform distribution compared to Łódź's more spatially clustered contamination (Table 1).

Spatial distribution and hotspot identification

Table 2 presents the spatial distribution and clustering of heavy metals across the urban landscape, complementing the raw concentrations reported in Table 1. The analysis identified specific patterns that are significantly connected to land use, notably regarding transportation and industrial activities. Kriging interpolation maps identified clear hotspots of Pb, zinc, and copper along major transportation corridors. These metals, connected to vehicle exhaust, tire degradation, brake components, and road abrasion, displayed higher levels in traffic zones, affirming that vehicular emissions as a major contributor. Pb (38–276 mg/kg) and Cu (36–151 mg/kg) showed localized contamination, while high Moran's I values (e.g., 0.64 for copper) indicated strong clustering, suggesting that mitigation should focus on densely populated corridors. Industrial zones displayed a contrasting pattern dominated by Cr, Ni and Co. Maximum concentrations reached 87 mg/kg for Cr, 62 mg/kg for Ni, and 49 mg/kg for Co, mainly around manufacturing plants and metal workshops. Moran's I values for Cr (0.55), Ni (0.57), and Co (0.60) confirmed significant spatial clustering, reflecting industrial emissions, runoff, and atmospheric deposition. Ongoing pollution in these regions necessitates focused actions like enhanced emission regulations and site-specific cleanup efforts. In contrast, Hg and As showed broader, more diffuse distributions. Concentrations were lower (0.02–0.76 mg/kg for Hg, 0.04–0.68 mg/kg for As) but extended citywide, likely influenced by long-range atmospheric deposition. Lower Moran's I values (0.48 for Hg, 0.43 for As) indicate dispersed patterns, emphasizing the need for citywide policies and emission controls.

Correlation analysis

The Pearson correlation analysis provided insights

Table 1: Descriptive statistics of heavy metal concentrations in urban soil samples (mg/kg)

Metal	Minimum	Maximum	Mean	Standard deviation (SD)	%CV
Cd	0.08	2.1	0.76	0.51	67.1
Pb	12.5	375	112.3	76.8	68.4
Cr	18.4	142.6	63.7	28.1	44.1
Cu	15.1	160.3	74.5	35.4	47.5
Zn	27.6	492.7	158.9	91.2	57.4
Ni	7.4	89.5	32.1	19.7	61.4
Co	4.3	36.2	18.5	8.2	44.3
Mn	174	693.5	331.6	102.9	31
As	1.2	35.7	14.6	7.3	50
Hg	0.03	0.9	0.31	0.18	58.1

Table 2: Summary of spatial distribution of heavy metals and hotspot identification

Metal	Zone of highest concentration	Concentration range (mg/kg)	Spatial pattern	Global Moran's I Value ($p < 0.01$)
Pb	Major transportation corridors	38 - 276	Clustered, hotspot near traffic zones	0.62
Zn	Major transportation corridors	47 - 158	Clustered, with high concentrations in traffic zones	0.59
Cu	Major transportation corridors	36 - 151	Clustered, hotspots near roads	0.64
Cr	Industrial zones	22 - 87	Concentrated near industrial areas	0.55
Ni	Industrial zones	14 - 62	Clustered near industrial sites	0.57
Co	Industrial zones	9-49	High in industrial zones	0.6
Hg	Diffuse distribution, city-wide	0.02 - 0.76	Diffuse, atmospheric deposition	0.48
As	Diffuse distribution, city-wide	0.04 - 0.68	Diffuse, atmospheric deposition	0.43

into potential sources and interrelationships among heavy metals in urban soils. Strong positive correlations were observed between Pb and Zn (r = 0.84), Cu and Zn (r = 0.79), and Cr and Ni (r = 0.82), suggesting common anthropogenic origins. These metals are generally associated with traffic emissions, wear from tires and brakes, industrial discharges and urban runoff. The strong Pb-Zn and Cu-Zn correlations likely reflect combined deposition from vehicular activity, while the Cr-Ni association points toward industrial operations, such as metal processing and electroplating, as major contributors. These patterns confirm trends in spatial distribution and underscore the necessity of focusing on particular pollution sources. Moderate correlations were observed between Hg and As (r = 0.56), indicating partially shared contamination sources. Given the diffuse spatial patterns of these elements, atmospheric deposition from fossil fuel combustion, small-scale industrial emissions, or legacy pesticide applications is a likely pathway. This moderate correlation implies that dispersion occurs at a regional level rather than from specific localized sources. Despite weaker association, Hg and As remain environmentally significant due to their toxicity and persistence. In contrast, Mn and Co exhibited weak or non-significant correlations with most metals; Mn had a maximum correlation of r = 0.33 with Co. This implies that Mn and Co primarily originate from geogenic or naturally occurring sources rather than anthropogenic activities. Mn reflects underlying soil geology, while Co variability is less influenced by shared contamination pathways compared to other metals. The correlation matrix (Table 3) complements spatial and statistical assessments, clustering metals into strong, moderate, and weakly associated groups. These classifications can facilitate the identification of pollution sources, spotting co-existing contaminants, and creating effective monitoring strategies. For example, Zn monitoring may provide indirect information on Pb and Cu due to their high interdependence, reducing analytical workload. On the contrary, metals that exhibit low correlation, like Mn and Co, point to the importance of management strategies that are centered on geological evaluations.

Principal component analysis

The PCA carried out in this study is a strong statistical tool designed to uncover the intricate sources of heavy metal pollution in urban soils. The analysis revealed three major principal components (PCs) that collectively explained 78.3% of the total variance in the dataset, indicating a high degree of structure and interpretability. PC1 alone accounted for 34.7% of the variance and was strongly influenced by Pb, Zn, and Cu, all of which are well-established tracers of vehicular emissions. Their high loading values; Pb (0.87), Zn (0.82), and Cu (0.79); reflect a shared origin, most likely from vehicle exhaust, brake pad wear, and tire degradation. This component corresponds with previous spatial analyses that recognized major roadways and transportation corridors as critical hotspots for these metals, implying that vehicular activity is a major factor in urban soil contamination. PC2 explained 27.1% of the total variance and exhibited high loadings for Cr, Ni, and Co, which are typically associated with industrial processes. Cr (0.85), Ni (0.83), and Co (0.76) all demonstrated strong interrelationships, suggesting emissions from similar anthropogenic activities such as metal processing, alloy manufacturing, and electroplating industries. The spatial distribution data reinforces these findings, revealing increased levels of these metals near industrial regions. This principal component underscores the localized but intense impact of industrial operations on soil contamination and points to the necessity of implementing stricter emission controls in such

Table 3: Pearson correlation coefficients between heavy metal concentrations in urban soils (n = 90).

Metal	Cd	Pb	Cr	Cu	Zn	Ni	Co	Mn
Cd	1	0.63	0.55	0.6	0.66	0.51	0.32	0.25
Pb	0.63	1	0.44	0.68	0.84	0.39	0.29	0.22
Cr	0.55	0.44	1	0.56	0.59	0.82	0.46	0.28
Cu	0.6	0.68	0.56	1	0.79	0.43	0.3	0.19
Zn	0.66	0.84	0.59	0.79	1	0.47	0.35	0.23
Ni	0.51	0.39	0.82	0.43	0.47	1	0.38	0.26
Co	0.32	0.29	0.46	0.3	0.35	0.38	1	0.33
Mn	0.25	0.22	0.28	0.19	0.23	0.26	0.33	1

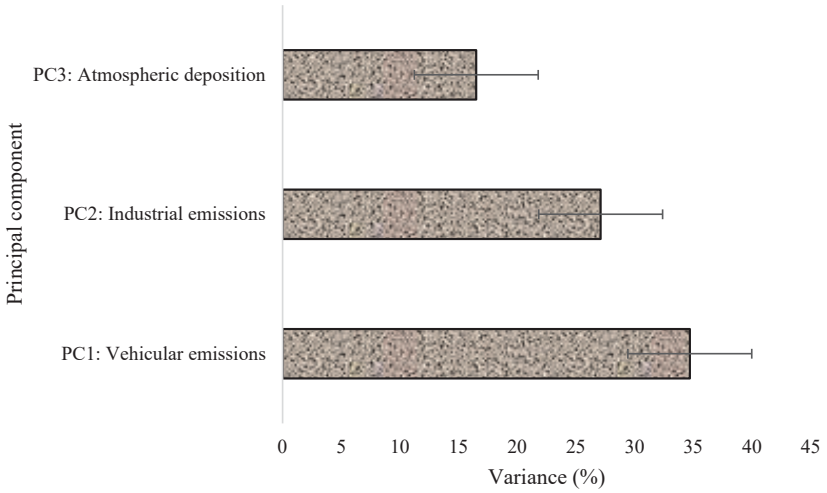


Fig. 4: PCA for heavy metal concentrations

areas. Furthermore, the presence of these metals in substantial amounts heightens concerns about both occupational and residential exposure for those living in proximity to industrial facilities. The third principal component (PC3), accounting for 16.5% of the variance, was primarily influenced by Hg and As, with exceptionally high loadings of 0.91 and 0.89, respectively. These components are usually released into the environment via atmospheric deposition caused by coal burning, pesticide application, and the long-distance movement of airborne pollutants. Unlike the localized patterns observed for vehicular and industrial metals, Hg and As were more diffusely distributed throughout the study area, as revealed in the spatial analysis. This widespread distribution suggests contributions from regional or even global sources and highlights the insidious nature of airborne pollutants. The close relationship between Hg and As in this component indicates a wider environmental concern, since both metals are harmful even in minimal amounts are likely to remain in the environment, presenting enduring threats to human health and ecological stability (Fig. 4).

The PCA results provide a comprehensive framework for interpreting the contamination profile of urban soils. Through the identification of specific elements related to vehicular, industrial, and atmospheric sources, the analysis provides a clearer insight into the sources of pollution and possible exposure routes. The clear separation of metals into these three categories reinforces previous findings from correlation and spatial analyses, lending robustness to the overall interpretation. Importantly, these insights are crucial for guiding environmental management strategies and policy interventions. As an illustration, pollution from traffic can be alleviated by using green buffers and regulating vehicle emissions, whereas industrial emissions call for focused remediation and tighter compliance standards. Addressing atmospheric deposition, however, may demand broader regional or international cooperation. Collectively, the PCA underscores the multifaceted nature of urban soil contamination and the need for integrated monitoring and control strategies (Table 4).

Source apportionment via positive matrix factorization (PMF)

The PMF model decomposed the heavy metal dataset into three distinct source profiles, consistent with PCA results. Traffic-related emissions (Factor 1) were the dominant contributor, accounting for 46% of the total metal burden, with Pb, Zn, and Cu as primary indicators. These metals are strongly associated with vehicle-related activities, including fuel combustion, brake wear, tire degradation, and engine oil leakage, consistent with observed hotspots identified near heavily trafficked areas. Industrial discharges (Factor 2) contributed 32% of the contamination load, characterized by high levels of Cr, Ni, and Co, commonly associated with metal finishing, electroplating, and

Table 4: Results of PCA for heavy metal concentrations

Principal Component	Heavy metal loadings
PC1: Vehicular emissions	Pb (0.87), Zn (0.82), Cu (0.79)
PC2: Industrial emissions	Cr (0.85), Ni (0.83), Co (0.76)
PC3: Atmospheric deposition	Hg (0.91), As (0.89)

Table 5: Source apportionment results from PMF for heavy metal concentrations in urban soils

Source	Factor	Contribution (%)	Dominant metals	Correlation (Observed vs. Reconstructed)
Traffic-related emissions	Factor 1	46%	Pb, Zn, Cu	r > 0.85
Industrial discharges	Factor 2	32%	Cr, Ni, Co	r > 0.85
Atmospheric deposition	Factor 3	22%	Hg, As	r > 0.85

alloy manufacturing. Their presence in industrial areas, along with the robust agreement found in PCA and spatial hotspot mapping, underscores the site-specific consequences of industrial activities and the urgent requirement for tighter emission regulations. Atmospheric deposition (Factor 3) accounted for the remaining 22%, dominated by Hg and As, which are introduced through fossil fuel combustion, pesticide use, and long-range transport of airborne pollutants. In contrast to the other elements, this source showed a diffuse spatial distribution, reflecting the effects of regional and transboundary contributions that are more difficult to control locally. Model validation showed strong correlations ($r > 0.85$) between observed and reconstructed concentrations, confirming the robustness of the PMF results. The integration of PMF, PCA, and spatial analysis provides a comprehensive understanding of heavy metal origins in urban soils. These quantified contributions provide support for evidence-based interventions, such as targeted traffic emission controls, more stringent industrial regulations, and regional air quality management strategies aimed at effectively reducing contamination (Table 5).

Human health risk assessment

The assessment of human health risks indicated significant disparities in vulnerability levels between children and adults, underscoring the heightened exposure risks that children experience as a result of their greater soil ingestion rates and enhanced physiological sensitivity. In the evaluated urban zones, hazard index (HI) values for children frequently exceeded the critical threshold of 1, particularly for Pb and As, indicating significant potential for non-carcinogenic effects. The highest risks were observed in industrial zones, where HI values reached 1.48 for Pb and 1.21 for As, while roadside areas also showed elevated risks. When assessed against international soil quality benchmarks, these metrics highlight substantial issues. As an illustration, the maximum permissible concentration (MPC) for lead (Pb) in Kazakhstan is set at 32 mg/kg, but the soil concentrations in high-exposure regions have been found to exceed this limit by up to 4.8 times. Similarly, As levels surpassed recommended thresholds outlined by the U.S. Environmental Protection Agency (0.5 mg/kg for residential soils) and Canadian guidelines (12 mg/kg), underscoring that children in industrial and roadside areas are exposed to metal concentrations well above safe limits. Comparable benchmarks from Europe, including Denmark (Pb: 40 mg/kg, As: 0.3 mg/kg) and the Netherlands (Pb: 85 mg/kg, As: 0.8 mg/kg), further reinforce the severity of these exceedances. The outcomes underscore the pressing requirement for focused mitigation actions, which include soil remediation, restricting children's access to polluted sites, and promoting community health education initiatives. For adults, HI values across all urban zones remained below the critical threshold of 1, suggesting a minimal likelihood of non-carcinogenic effects under current exposure scenarios. Nevertheless, moderately elevated HI values for Pb (0.73) and As (0.70) in industrial and roadside zones suggest that chronic or occupational exposure could still pose long-term health risks, particularly for sensitive populations such as pregnant individuals. In conjunction with non-carcinogenic risks, the carcinogenic risks related to As exposure were analyzed. Industrial and roadside areas exhibited

Table 6: Human health risk assessment for heavy metal contamination in urban soils, disaggregated by exposure pathway and population group

Zone	Metal	Exposure pathway	Child HI	Adult HI	Carcinogenic risk (CR): As
Industrial Zone	Pb	Ingestion	0.82	0.42	–
		Inhalation	0.31	0.18	–
		Dermal Contact	0.35	0.13	–
		Total (HI)	1.48	0.73	–
	As	Ingestion	0.7	0.31	1.3×10^{-4}
		Inhalation	0.25	0.12	1.3×10^{-4}
		Dermal Contact	0.26	0.11	1.3×10^{-4}
		Total (HI)	1.21	0.54	1.3×10^{-4}
Roadside Zone	Pb	Ingestion	0.77	0.39	–
		Inhalation	0.29	0.17	–
		Dermal Contact	0.32	0.14	–
		Total (HI)	1.38	0.7	–
	As	Ingestion	0.68	0.3	1.2×10^{-4}
		Inhalation	0.25	0.11	1.2×10^{-4}
		Dermal Contact	0.26	0.11	1.2×10^{-4}
		Total (HI)	1.19	0.52	1.2×10^{-4}
Recreational Zone	Pb	Ingestion	0.52	0.29	–
		Inhalation	0.19	0.12	–
		Dermal Contact	0.19	0.09	–
		Total (HI)	0.9	0.5	–
	As	Ingestion	0.45	0.25	1.1×10^{-4}
		Inhalation	0.16	0.08	1.1×10^{-4}
		Dermal Contact	0.14	0.07	1.1×10^{-4}
		Total (HI)	0.75	0.4	1.1×10^{-4}
Residential Zone	Pb	Ingestion	0.61	0.33	–
		Inhalation	0.22	0.14	–
		Dermal Contact	0.22	0.13	–
		Total (HI)	1.05	0.6	–
	As	Ingestion	0.51	0.26	1.2×10^{-4}
		Inhalation	0.19	0.1	1.2×10^{-4}
		Dermal Contact	0.15	0.09	1.2×10^{-4}
		Total (HI)	0.85	0.45	1.2×10^{-4}

risk levels of approximately 1.3×10^{-4}, marginally exceeding the U.S. EPA acceptable limit of 1×10^{-4}. While this marginal exceedance does not indicate immediate danger, it underscores potential long-term risks from sustained exposure and bioaccumulation. Considering As's strong associations with skin, lung, and bladder cancers, these findings highlight the importance of integrating carcinogenic risk factors into urban soil monitoring, public health initiatives, and risk management approaches (Table 6).

Ecological risk assessment

The ecological risk assessment of heavy metal contamination in urban soils revealed significant concerns, particularly in industrial and roadside zones, where PERI values were markedly elevated. Cd and Hg were the primary contributors, with PERI values of 212.7 and 174.3, and individual risk factors (Er_i) of 197.4 and 163.5, indicating moderate to high ecological risk. These values reflect intense anthropogenic pressures, including industrial emissions and vehicular exhaust. Cadmium negatively impacts soil microbial communities, lowers fertility, and can seep into groundwater. In contrast, Hg is neurotoxic and likely to biomagnify through food chains, creating risks to both humans and wildlife. The Geoaccumulation Index (Igeo) further highlighted contamination patterns, identifying Pb and Zn as major pollutants, with over 25% of sampled sites in industrial and roadside zones classified as moderately to heavily polluted. Elevated concentrations of Cr, Ni, and Co were observed in industrial zones, attributed to metal processing and industrial runoff, whereas roadside locations were characterized by Pb, Zn, and Cu, which are reflective of emissions from traffic. Hg and As exhibited a more diffuse

Table 7: Ecological risk assessment for heavy metal contamination in urban soils.

Zone	Metal	PERI Value	Er_i (Cd)	Er_i (Hg)	Igeo classification (Pb)	Igeo classification (Zn)
Industrial Zone	Cd	212.7	197.4	-	Moderately to heavily polluted	-
	Hg	174.3	-	163.5	-	-
Roadside Zone	Cd	188.9	176.8	-	Moderately polluted	-
	Hg	149.8	-	136.7	-	-
Recreational Zone	Cd	68.4	82.3	-	Low to moderate pollution	Low pollution
	Hg	58.6	-	71.1	-	-
Residential Zone	Cd	114.6	128.7	-	Low to moderate pollution	Low pollution
	Hg	101.2	-	119.8	-	-

distribution, indicating contributions from long-range atmospheric deposition and small-scale industry. The implications of these findings are evident for land management, cleanup strategies, and public governance. Areas with very high ecological risk should be prioritized for restricted or controlled land uses, avoiding residential, recreational, or agricultural development without prior remediation. Remediation strategies such as phytoremediation and the use of soil amendments, can help decrease metal bioavailability, and consistent soil monitoring is necessary to assess the effectiveness of these interventions. Stronger enforcement of industrial emission standards and traffic-related pollution controls, integrated with urban planning, will help prevent further contamination. This assessment establishes a framework for informed decision-making by connecting numerical risk indices to actionable management strategies, thereby safeguarding both ecosystem and public health in Astana (Table 7).

Impacts of heavy metal contamination on soil microbial activity

The MBC values indicate a clear gradient of declining soil microbial activity across different land-use types, reflecting the impact of heavy metal contamination. The highest MBC was recorded in peri-urban reference soils (312.7 ± 23.6 milligrams of carbon per kilogram of soil (mg C/kg)), suggesting healthy and active microbial communities in less-disturbed areas. Recreational areas maintained moderately high MBC levels (259.4 ± 19.1 mg C/kg), indicating relatively low anthropogenic influence. In contrast, residential soils exhibited reduced microbial biomass (187.9 ± 16.4 mg C/kg), likely due to increasing urban pressures. The lowest MBC values were observed in industrial (126.4 ± 12.3 mg C/kg) and roadside soils (109.2 ± 11.2 mg C/kg), coinciding with higher enrichment of Pb, Cd, and Hg. These findings reveal that elevated heavy metal levels greatly diminish microbial biomass, potentially jeopardizing soil health, nutrient cycling, and the overall functioning of ecosystems in highly urbanized regions (Fig. 5).

The results for basal soil respiration (BSR) and DHA indicate a significant adverse effect of heavy metal pollution on soil microbial activity across various land-use categories. Peri-urban reference soils exhibited the highest BSR (2.87 mg CO_2-C/kg/d) and DHA (3.12 µg TPF·g/h), indicating healthy microbial activity. Residential soils showed moderate reductions in BSR (1.96 mg CO_2-C/kg/d) and DHA (1.88 µg TPF·g/h), while industrial and roadside soils recorded the lowest BSR (~1.5 mg CO_2-C/kg/d) alongside severely suppressed DHA (~1.0 µg TPF·g/h). These results suggest that increased levels of heavy metals in urban areas significantly hinder microbial metabolism and enzyme function, which may lead to disruptions in soil fertility and nutrient cycling (Table 8).

The findings regarding heavy metal levels in urban soils highlight the considerable effect of human activities, particularly in regions affected by vehicle emissions, industrial waste, and atmospheric deposition. Elevated levels of Pb, Zn, Cu, Cr, Ni, and As were predominantly observed in roadside and industrial zones, indicating that urban soils act as reservoirs for these contaminants. This spatial variability reflects complex interactions between pollution sources and the urban environment. As noted by Duan *et al*. (2024), this heterogeneity is frequently influenced by the interactive effects of spatial drivers, with combinations of environmental variables providing more significant explanatory power regarding heavy metal distribution compared to isolated factors. Their integration of Geodetector,

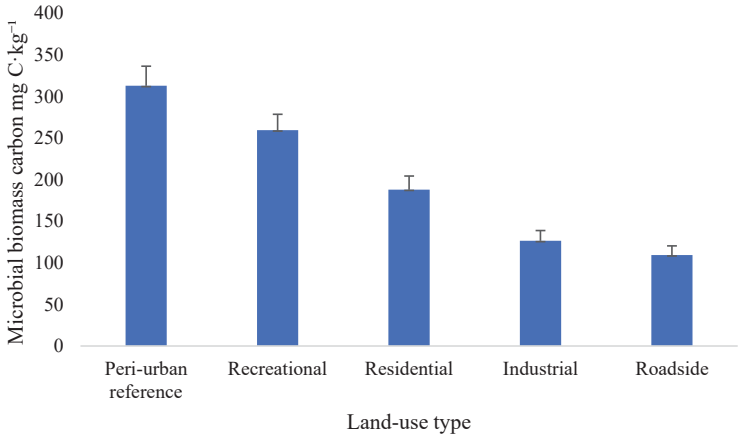


Fig. 5: Microbial biomass carbon by land-use

Table 8: Effects of heavy metal contamination on soil microbial activity across different land-use types (mean ± standard deviation)

Land-use type	Basal soil respiration (milligrams of carbon dioxide–carbon per kilogram of soil per day)	Dehydrogenase activity (micrograms of triphenyl formazan per gram of soil per hour)	Percentage reduction in basal soil respiration relative to reference
Peri-urban reference	2.87 ± 0.15	3.12 ± 0.22	0
Recreational	2.42 ± 0.13	2.81 ± 0.20	15.7
Residential	1.96 ± 0.12	1.88 ± 0.12	31.7
Industrial	1.51 ± 0.10	1.12 ± 0.11	47.4
Roadside	1.49 ± 0.09	0.91 ± 0.10	48.1

Categorical Boosting (CatBoost), and SHapley Additive exPlanations (SHAP) techniques highlighted that metal distributions, particularly for Hg, Cd, and Zn, were shaped by source–flow–sink interactions and that these interactions vary in influence across space. Similarly, Feng *et al.* (2024), reported in Cangxi County that spatial patterns of Pb, Zn, Cr, and Ni were closely interconnected, with higher levels connected to human activities, especially in regions marked by intense agricultural and traffic engagement. Their source apportionment via PMF further supported the significance of transportation (30.64%) and mixed agricultural traffic sources (65.2%) as key contributors. The current study's observations are supported by these findings, which indicate that traffic and industrial emissions are the main contributors to urban soil contamination, underscoring the importance of implementing spatially explicit monitoring systems and advanced modeling tools to analyze pollutant dynamics. The integration of such approaches can enhance our understanding of contaminant interactions and inform targeted urban soil pollution management strategies. The spatial distribution of heavy metals in urban soils, as determined through geostatistical and spatial analysis, reveals distinct contamination gradients that align closely with land-use types and the proximity to industrial activities or high-traffic zones. In regions characterized by high levels of industrial activity and vehicle emissions, elevated levels of elements like Cd, Pb, and Zn are regularly detected, highlighting the significant impact of human activities on soil quality. For instance, Wang *et al.* (2020), reported that in Jiangsu Province, China, heavy metals exhibited both zonal and clustered spatial distributions, with high levels concentrated in industrial parks and developed urban centers along the Yangtze River; patterns strongly correlated with the distribution of industrial enterprises. This spatial connection emphasizes the crucial influence of industrialization in forming contamination profiles. Similarly, Ma *et al.* (2023), demonstrated that at non-

ferrous metal smelting sites, factors such as the proximity to sintering workshops, raw material yards, and electrolyzers significantly influenced the horizontal distribution of heavy metals like As, Cd, and Hg. In the vertical dimension, physicochemical properties such as soil moisture, pH, and lithology also played important roles. These results suggest that spatial variability is influenced not just by emission sources but also by subsurface conditions that control the movement and retention of pollutants. The PCA served as a critical analytical tool in identifying the predominant sources of heavy metal contamination in urban soils, revealing three principal contributors: vehicular emissions, industrial discharges, and atmospheric deposition. The findings underscored the leading role of vehicular emissions in contributing to soil pollution, in agreement with prior research that emphasizes the substantial influence of traffic-related pollutants on both soil and air quality in urbanized regions. For instance, Ghose *et al.* (2004), documented that vehicular emissions in Kolkata exceeded permissible levels for key pollutants, severely degrading air quality and threatening public health. Similarly, Zhang and Batterman (2013), demonstrated that traffic congestion not only elevated nitrogen dioxide (NO_2) concentrations near roadways but also increased morbidity and mortality risks for exposed populations. The identification of industrial emissions as a secondary but substantial source further corroborates findings from urban and peri-urban industrial zones, where localized discharges contribute to heavy metal deposition (Sanad *et al.*, 2025). Industrial activities often emit metals such as Pb, Cd, and As, which accumulate in adjacent soils and present long-term ecological and human health risks (Angon *et al.*, 2024). Despite its smaller share of the variance, atmospheric deposition, which comes from the long-range transport of pollutants, has been identified as a notable contributor, highlighting the broader environmental implications of air pollution. The application of the Positive Matrix Factorization (PMF) model strengthened the results obtained from the PCA by providing a more detailed and quantitative apportionment of heavy metal sources in urban soils. Both models consistently identified traffic-related emissions, industrial discharges, and atmospheric deposition as the principal contributors to contamination, highlighting the robustness and complementarity of the multivariate techniques. Moreover, PMF identified traffic-related emissions as the leading contributor to the heavy metal burden, further supporting the expanding evidence that points to vehicles as a major source of urban pollutants. This aligns with recent studies, such as Tafidis *et al.* (2024), which demonstrated that fine particulate matter ($PM_{2.5}$) concentrations in Dublin were significantly influenced by urban traffic dynamics, with Gaussian Process Regression models identifying spatial proximity to intersections as a key predictor of pollutant levels. Furthermore, Reche *et al*. (2022), indicated that municipalities with inadequate non-motorized transport systems and poor public transport accessibility had higher levels of $PM_{2.5}$ and NO_2 from traffic, contributing to discernible health issues. The PMF model's strong correlation between observed and reconstructed heavy metal concentrations further validates its reliability for source attribution. These findings emphasize the need for targeted emission control strategies, particularly focusing on urban traffic management. As highlighted by Rautela and Goyal (2024), integrating advanced forecasting tools such as AI and machine learning can improve spatial-temporal pollution assessment and support the design of context-specific mitigation strategies. Consequently, thorough interventions, such as minimizing traffic emissions, managing industrial waste, and utilizing intelligent pollution monitoring technologies, could greatly alleviate soil and air contamination in city settings. Moreover, the study underscores substantial human health and ecological risks associated with heavy metal contamination in urban soils, particularly affecting children due to their higher soil ingestion rates and lower body mass. Consistent with findings from Shetty *et al.* (2024), elevated hazard index (HI) values for Pb and As in high-exposure areas, such as industrial and roadside zones, indicate significant non-carcinogenic and marginal carcinogenic risks, necessitating urgent public health interventions in sensitive locations like schoolyards and residential areas near major roads. From an ecological standpoint, increased concentrations of Cd and Hg were linked to moderate to high potential ecological risk index (PERI) values, supporting findings by Caković *et al*. (2021), which indicated that Cd surpassed allowable levels in all analyzed soils of protected natural reserves, designating extensive

regions as high ecological risk areas. Over 25% of sampled urban sites in the present study were categorized as "moderately to heavily polluted" by Pb and Zn, highlighting potential long-term degradation of soil functions and biodiversity. The integration of risk indices, land use data, and PMF source contributions in spatial analysis has identified contamination hotspots close to highways, industrial facilities, and densely populated urban regions. This geostatistical-spatial risk mapping approach aligns with methodologies employed in southern Italy by Ducci *et al.* (2017), who applied an integrated environmental characterization strategy to delineate risk zones across heterogeneous land uses. The attribution of these contamination patterns predominantly to anthropogenic sources; such as vehicular emissions and industrial discharges; is further supported by probabilistic receptor modeling and Monte Carlo simulations, as applied in the study by Alsafran *et al.* (2021), which found that consumption of leafy vegetables grown in polluted soils posed significant non-carcinogenic and carcinogenic risks due to elevated levels of As, Cr, and Ni.

CONCLUSION

This study delivers compelling evidence indicating that urban soils in rapidly evolving cities are profoundly affected by heavy metal contamination, with human-driven activities including vehicle exhaust, industrial functions, and urban building identified as the primary causes. The integration of advanced spatial mapping, source apportionment using PCA and PMF, and comprehensive ecological and human health risk assessments allowed for a detailed understanding of both the distribution patterns and the potential impacts of heavy metals across different land-use types. The results revealed notably elevated concentrations of toxic metals, including Pb, Cd, and Hg, especially in high-traffic and industrial zones, which pose substantial risks to human health, with children and other vulnerable populations being particularly susceptible, as well as to soil quality and broader ecosystem integrity. The recognized spatial inconsistency of contamination points out that risks are not evenly distributed in urban settings, stressing the vital importance of site-specific mitigation approaches. Areas characterized by mixed industrial and residential land use demonstrated the highest cumulative contamination indices, suggesting synergistic effects from multiple pollution sources that necessitate targeted monitoring and remediation. This study highlights the significance of merging geostatistical modeling with multivariate source identification and risk assessment frameworks, offering a solid, data-driven basis for managing urban environments. Such integration facilitates the prioritization of high-risk zones, optimizes the allocation of remediation resources, and supports informed decision-making in urban planning and environmental regulation. Furthermore, the study underscores the extensive applicability of these techniques to other swiftly urbanizing regions globally, presenting a transferable framework for the assessment, mapping, and management of urban soil contamination. The results highlight an urgent need for policy interventions, including stricter emission controls for vehicles and industries, improved industrial waste management, sustainable urban planning that considers soil quality preservation, and the adoption of soil remediation programs tailored to local contamination patterns. In parallel, fostering public awareness, encouraging community participation in pollution reduction initiatives, and promoting safe urban agricultural practices can significantly reduce human exposure to toxic metals. Prompt and sustained interventions, driven by scientific findings, are imperative to alleviate risks, defend public health, conserve ecosystem services, and secure the lasting sustainability of urban landscapes in response to fast-paced urbanization and industrial development. Feasible remediation strategies include phytoremediation using metal-accumulating plants, soil amendments to immobilize bioavailable metals, and restriction of sensitive land uses in identified hotspots. Economic feasibility is favorable given low-cost phytoremediation options and urban green space integration. Sustainable urban planning, involving emission controls, zoning regulations, and persistent monitoring, plays a vital role in alleviating additional contamination. Scenario analysis indicates that without interventions, projected urban expansion and industrial growth will exacerbate contamination hotspots, increase human exposure, and compromise soil ecosystem services.

AUTHOR CONTRIBUTIONS

A. Zandybay conceptualized the study, designed

the sampling framework, and coordinated field data collection. A. Kydyrova performed laboratory analyses, including heavy metal digestion and ICP-MS measurements, and assisted in data validation. A. Karilkhan conducted spatial analysis, developed geostatistical models, and supported interpretation of results. S. Gulnur contributed to statistical modeling, including PCA, HCA, and PMF analyses, and assisted in figure preparation. A. Daribay participated in ecological and human health risk assessments and helped draft sections of the results. T. Mkilima, the corresponding author, supervised the study, guided data interpretation, critically revised the manuscript, and finalized it for submission.

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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.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
%CV	Percentage coefficient of variation
ADI	Average daily intake
ArcGIS	Aeronautical reconnaissance coverage geographic information system
As	Arsenic
B_n	Geochemical background concentration
CatBoost	Categorical Boosting
Cd	Cadmium
C_n	Measured concentration of metal in soil
cm	Centimeter
Co	Cobalt
Cr	Chromium
CR	Carcinogenic risk
CSF	Cancer slope factor
Cu	Copper
Er_i	Individual ecological risk factor
FW	Freshwater
g	Gram
GIS	Geographic information system
GPS	Global positioning system
GRSP	Glomalin-related soil proteins
g/m^2	Grams per square meter
HCA	Hierarchical cluster analysis
Hg	Mercury
HCl	Hydrochloric acid
HI	Hazard index
HNO_3	Nitric acid
HQ	Hazard quotient

IBM	International business machines
ICP-MS	Inductively coupled plasma mass spectrometry
Igeo	Geoaccumulation index
KMO	Kaiser-meyer-olkin
kg	Kilogram
L	Liter
log_2	Base-2 logarithm
m	Meter
mg	Milligram
mg/kg	Milligram per kilogram
Mn	Manganese
mL	Milliliter
MΩ·cm	Megaohm-centimeter
n	Sample size indicator
Ni	Nickel
NIST	National Institute of Standards and Technology
NO_2	Nitrogen dioxide
PCA	Principal component analysis
Pb	Lead
PERI	Potential ecological risk index
pH	Potential of hydrogen
PLI	Pollution load index
PM	Particulate matter
PM2.5	Particulate matter ≤ 2.5 micrometers
PM10	Particulate Matter ≤ 10 micrometers
PMF	Positive matrix factorization
RAGS	Risk assessment guidance for superfund
RSD	Relative standard deviation
RMSE	Root mean square error
SHAP	SHapley Additive exPlanations
SPSS	Statistical package for the social sciences
SRM	Standard reference material
USA	United States of America
USEPA	United States Environmental Protection Agency
v/v	Volume per volume
Zn	Zinc

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ORIGINAL RESEARCH PAPER

Eco-friendly development of biocomposite films from Durio zibethinus Murr. seeds reinforced with nanocellulose and functional carrageenan additives

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ABSTRACT

BACKGROUND AND OBJECTIVES: The increasing concern over plastic pollution has driven the search for biodegradable and sustainable alternatives derived from renewable polysaccharides. However, films made from starch generally exhibit poor mechanical strength, high water sensitivity, and low thermal resistance. Durian seed starch, is an underutilized agricultural by-product that holds great potential as a film-forming matrix but has rarely been explored. To address its limitations, the study objectives were to develop and optimize composite films from durian seed.

METHODS: A statistical optimization approach based on Box–Behnken design under response surface methodology was employed to investigate the effects of starch, carrageenan, and nanocrystalline cellulose on film performance. Mechanical properties were evaluated (tensile strength and elongation at break) as the main response variables. Seventeen experimental runs were conducted, and the model was statistically validated to identify significant effects and interactions among the variables. The optimum film was selected and further characterized using Fourier-transform infrared spectroscopy to evaluate functional groups, X-ray diffraction to assess crystallinity, scanning electron microscopy to examine morphology, and thermogravimetric analysis to determine thermal stability. Thickness and swelling behavior were also measured to evaluate dimensional stability.

FINDINGS: Run 9 was identified as the optimum formulation, achieving a tensile strength of 2.32 mega pascal, an elongation at break of 44.94 percent, and the lowest swelling ratio of 142.39 percent. Carrageenan stabilized the starch suspension, enabling smooth film formation, while nanocrystalline cellulose reinforced the composite network by improving compactness, crystallinity, and interfacial hydrogen bonding. X-ray diffraction revealed an increase in crystallinity index from 48.14 to 55.42 percent, surface morhology showed a denser and more homogeneous morphology with fewer voids, and thermogravimetric analysis demonstrated improved thermal resistance due to restricted chain mobility and enhanced char formation.

CONCLUSION: This study represents the first systematic attempt to valorize durian seed into functional biocomposite films reinforced with carrageenan and nanocrystalline cellulose. The synergistic roles of carrageenan and nanocrystalline cellulose effectively tailored structural integrity and functional properties, overcoming the common drawbacks of starch-based films. The findings highlight the potential of transforming underutilized durian seed biomass into biodegradable packaging materials, thereby contributing to sustainable strategies for reducing plastic waste.

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INTRODUCTION

The increasing environmental concerns over synthetic plastic pollution have accelerated the development of biodegradable and renewable polymeric films for food packaging and other applications (Gilani *et al.,* 2023). Polysaccharide-based films have attracted considerable attention as sustainable alternatives to synthetic plastics due to their biodegradability, renewability, and non-toxicity (Behrooznia and Nourmohammadi, 2024). Among the commonly studied polysaccharides, cellulose, chitosan, polylactic acid (PLA) from lactic acid and starch have been widely used to fabricate biodegradable films (Hidayat *et al.,* 2025; Kacaribu *et al.,* 2025b, 2025a; Kacaribu and Darwin, 2024; Yulianto *et al.,* 2023). Starch, in particular, has emerged as one of the most promising candidates due to its abundance, low cost, ease of extraction, and environmentally friendly processing (Singh *et al.,* 2024). However, films prepared from native starch generally exhibit poor mechanical strength and high water sensitivity which limit their practical applications (Arruda *et al.,* 2025). Durian seeds (*Durio zibethinus* Murr.) are an underutilized agricultural by-product rich in starch and other compound (Baraheng and Karrila, 2019; Gamay *et al.,* 2024). Their starch content makes it as a potentially valuable raw material for biopolymer film production (Rahmawati *et al.,* 2022). In tropical regions such as Indonesia, durian seeds are abundantly available as agro-waste from the fruit processing. Although durian seeds are technically edible, they are not considered a staple food source and are often discarded after fruit consumption. Compared with cassava, corn, or potato starches—widely used for food and industrial purposes—durian seed starch offers a low-cost, underutilized, and sustainable alternative. This makes durian seed starch a promising and economically viable raw material for developing biodegradable biopolymer films, particularly in regions with abundant durian production. From an environmental standpoint, utilizing durian seed starch contributes to waste valorization by converting an abundant agro-industrial by-product into value-added biodegradable materials. This approach supports circular bioeconomy principles by minimizing organic waste and reducing dependence on food-grade starch sources such as cassava and corn. Moreover, the film fabrication process employed in this study uses water-based formulations without toxic solvents, ensuring minimal environmental burden and complete biodegradability of the final product. Therefore, the use of durian seed starch not only offers a sustainable material alternative but also promotes responsible waste management and resource efficiency in tropical agricultural regions. However, when processed into aqueous suspensions, durian seed starch tends to form gels with high viscosity, hindering uniform film casting and reducing the resulting films' mechanical quality. Carrageenan, a sulphated polysaccharide derived from red seaweeds, can be incorporated into durian seed starch suspensions to act as a film-forming aid to overcome this limitation. Carrageenan can modify the rheological behavior of the suspension, prevent excessive gelation and enable the formation of stable, continuous films (Hidayat *et al.,* 2025). In addition to its gel-forming ability, carrageenan is selected because it is biodegradable, food-safe, and capable of forming intermolecular hydrogen bonds with starch chains (Goiana *et al.,* 2025), thereby improving film homogeneity and flexibility. Further improvement of film performance can be achieved by incorporating nanocrystalline cellulose (NCC) as a reinforcing filler. NCC possesses high crystallinity, large specific surface area, and excellent mechanical properties, which can significantly enhance starch-based films' tensile strength, barrier properties, and thermal stability through strong hydrogen bonding interactions within the polymer network (Alsufyani and M'sakni, 2023; Thipchai *et al.,* 2023). NCC was chosen over other nanoscale fillers (such as nanoclays or metal oxides) because of its renewable origin, biocompatibility, and ability to reinforce biopolymer matrices without compromising biodegradability. Previous studies have reported the enhancement of starch-based films by adding carrageenan or nanocellulose individually (Hu *et al.,* 2025; Yap *et al.,* 2024). These approaches have improved mechanical performance, water resistance, and functional activities. However, most research has been conducted using starches from cassava (González *et al.,* 2024), corn (Abotbina *et al.,* 2021), or potato (Moreno *et al.,* 2025), and little attention has been given to using durian seed starch. Moreover, the combined use of carrageenan as a film-forming functional additive and NCC as a reinforcing filler in durian seed starch films has not yet been systematically investigated. Although

carrageenan and NCC have individually demonstrated great potential in improving starch-based films, their combined effects within a durian seed starch matrix have not yet been systematically investigated. In particular, no previous studies have explored how carrageenan can modulate the rheology of durian seed starch suspensions to facilitate stable film formation while nanocrystalline cellulose reinforces the resulting network to enhance structural integrity, barrier performance, and thermal stability. This knowledge gap highlights the need to understand their possible synergistic interaction in creating high-performance, biodegradable films derived from non-food, underutilized starch sources. The synergistic effects of these additives in a durian seed-based matrix remain unknown, and their optimization using response surface methodology (RSM) with a box behnken design (BBD) has not been reported. The scientific novelty of this work lies in the hypothesized synergistic interaction among starch, carrageenan, and nanocrystalline cellulose. Carrageenan modulates the starch matrix through hydrogen bonding, improving film continuity, while nanocrystalline cellulose reinforces the network by forming additional intermolecular bonds, resulting in a compact and stable polymer structure. This study, aimed to develop and characterize biodegradable composite films from durian seed starch with carrageenan and NCC, and to optimize their formulation and processing conditions using RSM–BBD to achieve biodegradable films suitable for sustainable applications. The present study focuses on structural and thermal behavior characterization. This study has been carried out in Institut Teknologi Sumatra, Lampung, Indonesia, in 2025.

MATERIALS AND METHODS

Materials

Commercial durian seed starch (referred to as durian seed starch flour) was used in this study to minimize variability arising from differences in durian varieties (Brand: Hasil Bumiku, Yogyakarta, Indonesia). NCC was supplied by AMI Scientific, Indonesia. Analytical-grade carrageenan and distilled water were used in all experiments.

Preparations of composite films

The composite films were prepared following the procedure described by Hidayat *et al.,* (2025) with slight modifications. The durian seed starch was weighed according to the experimental design and dispersed in distilled water. The suspension was stirred using a magnetic stirrer at 60 revolutions per minute (rpm) and heated on a hot plate at 90 degrees Celsius (°C) for 20 minutes (min) to allow starch gelatinization. Carrageenan and NCC were then added according to the formulation design, and the mixture was stirred for an additional 10 min under the same conditions to ensure homogeneity. The resulting film-forming suspension was poured into a 20 centimeters (cm) × 20 cm glass mold and leveled to achieve uniform thickness. The films were dried in a hot-air oven at 60 °C for 24 hours (h), after which the specimens were removed from the molds and conditioned in a desiccator prior to characterization (Hidayat *et al.,* 2025).

Experimental design

The RSM was employed to design and analyze the experiments using Design-Expert software (Version 12, Stat-Ease Inc., Minneapolis, USA). A BBD was applied with three independent variables to evaluate response trends and identify the optimal formulation. BBD was employed because it provides an efficient and economical approach for modeling second-order responses while minimizing the number of required experimental runs. In the present study, the independent variables were the concentrations of durian seed starch, NCC, and carrageenan percent (%) (Table 1). The selection of concentration ranges for these components was based on previous studies (Hidayat *et al.,* 2025) and preliminary trials, which

Tabel 1: Experimental design of preparation of film composite

Independent variables	Unit	Level		
		-1	0	+1
Durian seed starch	%	4	5	6
Carrageenan	%	1	2	3
NCC	%	0.5	1	1.5

demonstrated their significant influence on film homogeneity (Data not shown). The chosen ranges ensured that the film-forming suspensions remained stable and castable without excessive gelation or brittleness The plasticizer glycerol was added at a fixed ratio of 5% (w/w of starch) in all formulations to maintain film flexibility. The response variables were tensile strength (TS) and elongation at break (EAB). The number of required experimental runs was determined using the polynomial Equation presented in Eq. 1. (Hidayat *et al.,* 2025):

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{13} AC + \beta_{23} BC + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2 + \varepsilon \quad (1)$$

where: Y represents the predicted response; β_0 is the intercept (offset value); β_1, β_2, β_3 are the linear coefficients; β_{11}, β_{22}, β_{33} are the quadratic coefficients; β_{12}, β_{13}, β_{23} are the interaction coefficients; A, B, C are the independent variables; and ε is the random error. The quadratic and interaction terms (A^2, B^2, C^2, AB, AC, BC) account for curvature and synergistic effects among factors.

Analytical analysis

The composite was characterized to evaluate its physical and chemical properties. Film thickness was measured at three different points using a digital micrometer, and the thickness was expressed as the mean ± standard deviation of the measurements. Swelling power was determined by immersing film samples (2 × 2 cm) in distilled water for 2 h at room temperature, following a standard method. Swelling power was calculated using Eq. 2 (Kacaribu *et al.,* 2025b):

$$\text{Swelling power (\%)} = \frac{W_t - W_0}{W_0} \times 100 \quad (2)$$

Where, W_0 is the initial dry weight of the film in gram (g), and Wt is the weight of the film composite after immersion (g).

Functional group analysis was performed using fourier transform infrared spectroscopy (FTIR) with an FTIR-650 instrument (Tianjin Gangdong Technology Development Co., Ltd., China). FTIR spectroscopy was used to detect molecular interactions among starch, carrageenan, and NCC. The crystalline structure and molecular ordering of the films were examined using x-ray diffraction (XRD) to determine changes in crystallinity after carrageenan and NCC incorporation. The measurements were carried out using a PANalytical X'Pert PRO diffractometer (Malvern Panalytical, Netherlands) equipped with Cu Kα radiation (λ = 1.5406 Å) operated at 40 kV and 30 mA. Diffraction patterns were recorded in the 2θ range of 10°–80°, with a step size of 0.02° and a scanning rate of 2°/min. The crystallinity index (CrI) was calculated using the Segal method to compare the relative proportion of crystalline to amorphous regions among the films (Segal *et al.,* 1959). Morphological analysis was conducted using scanning electron microscopy (SEM, JEOL JSM 6390 LA) at an accelerating voltage of 10 or 15 kV. SEM imaging examined the film morphology and filler dispersion. Thermal properties of the composite were analyzed using a thermogravimetric analyzer (TGA), derivative thermogravimetric (DTG), and differential thermal analysis (DTA) which samples were heated from 0 °C to 500 °C at 10 °C/min under a nitrogen atmosphere, to assessed thermal stability and degradation behavior. Mechanical properties were evaluated according to the ASTM D882-18 standard, where tensile strength was measured at a 50 mm/min crosshead speed. The TS and EAB were calculated using Eqs. 3 and 4, respectively (Sasria *et al.,* 2025):

$$\text{TS (MPa)} = \frac{F_{max}}{A} \quad (3)$$

$$\text{EAB (\%)} = \frac{L_f - L_0}{L_0} \times 100 \quad (4)$$

Where, MPa is mega pascal, F_{max} is the maximum force applied to the specimen before breaking (N), A is the initial cross-sectional area of the film as square millimeter (mm^2), L_f is the film length at breaking point as millimeter (mm), and L_0 is the initial film length (mm).

RESULTS AND DISCUSSION

Experimental result and model fitting

The presents study applied the BBD to evaluate the effects of the selected independent variables (A, B, C) on the TS and EAB of regenerated durian seed based films. The BBD (17 runs) produced TS values ranging from 1.04 to 2.32 MPa and EAB values from 34.73 to 58.78%, reflecting clear formulation effects on both responses. The average TS was 1.40 MPa (coefficient

Table 2: Experimental run obtained

Run	Factors			Responses	
	A: Seed Durio zibethinus Murr. (%)	B: Carrageenan (%)	C:NCC (%)	Tensile Strength (MPa)	EAB (%)
1	5	2	1	1.4225	46.51
2	5	1	0.5	1.0425	44.25
3	4	3	1	1.3239	56.41
4	5	2	1	1.4245	46.97
5	5	2	1	1.3952	40.11
6	5	3	0.5	1.3507	54.22
7	4	2	0.5	1.3404	52.54
8	5	2	1	1.2798	47.34
9	6	2	1.5	2.3246	44.94
10	4	2	1.5	1.1882	34.78
11	5	1	1.5	2.0132	41.61
12	6	2	0.5	1.0894	42.99
13	5	2	1	1.5839	49.14
14	5	3	1.5	1.3757	58.78
15	4	1	1	1.2076	38.24
16	6	1	1	1.1175	34.73
17	6	3	1	1.3802	53.31

of variation, CV = 12.53%), while the average EAB was 46.24% (CV = 2.67%). A quadratic model was retained for both responses based on model summary statistics and lack-of-fit diagnostics. For TS, the coefficient of determination (R^2 = 0.8711) and adjusted R^2 (0.7053) indicated that approximately 87% of the data variability was explained by the model, while some residual variation could be attributed to experimental noise during film preparation and measurement. Although the predicted R^2 (−0.6572) was notably lower than the adjusted R^2, the adequate precision (adeq. Precision) (9.311) and non-significant lack-of-fit (p = 0.0822) supported that the quadratic model still captured the overall trend of the experimental responses. The relatively high PRESS value (2.78) also reflects the inherent data dispersion but remains within an acceptable level for empirical RSM models with small datasets. Therefore, despite moderate predictive strength, the quadratic model was considered appropriate for analyzing the main and interaction effects among variables. For EAB, R^2 = 0.9716, adjusted R^2 = 0.9351, and a high adeq. precision value (16.326) with non-significant lack-of-fit (p = 0.2395) demonstrated that the model exhibited excellent accuracy and prediction reliability. These results confirm the adequacy of the quadratic polynomial in describing the response behavior of both tensile strength and elongation at break. The adeq. precision and lack-of-fit tests further confirm the reliability of the developed model. An adequate precision value greater than 4 indicates that the model has a sufficient signal-to-noise ratio, suggesting that it can be used to navigate the design space effectively. In this study, both TS (9.311) and EAB (16.326) exceeded this threshold, demonstrating a high level of model responsiveness to factor changes. Meanwhile, the non-significant lack-of-fit ($p > 0.05$) for both responses indicates that the deviation between the predicted and actual values was mainly due to random error rather than systematic bias, confirming that the quadratic model adequately represents the experimental data as Presented in Table 3.

ANOVA and term significance

The TS model was statistically significant (Model Fisher's variance ration/F = 5.26, p = 0.0199). Significant terms were C (NCC), AC, and BC ($p < 0.05$) (Table 3), indicating that NCC drives TS and that its effect depends on starch and carrageenan levels. Other linear and quadratic terms were not significant; the lack-of-fit was not significant (p = 0.0822). For EAB, the model was highly significant (Model F = 26.60, $p < 0.0001$), with A (starch), B (carrageenan), and quadratic terms (B^2) as significant contributors (Table 3). This pattern shows that carrageenan dominates film extensibility with a strong curvature (quadratic) along B; starch also contributes positively, whereas NCC was not significant in the main effect

Table 3: ANOVA for the fitted quadratic models of TS and EAB

Paramaters	TS (Mpa)	EAB (%)
Std. Dev.	0.18	1.23
Mean	1.40	46.24
F-value	5.26	26.60
p-value	0.0199	0.0001
lack-of-fit	0.0822	0.2395
C.V. %	12.53	2.67
PRESS	2.78	111.24
-2 Log Likelihood	-25.94	40.31
R-Squared	0.8711	0.9716
Adj R-Squared	0.7053	0.9351
Pred R-Squared	-0.6572	0.7035
Adeq Precision	9.311	16.326
Bayesian information criterion (BIC)	2.39	68.64
Corrected akaike information criterion (AICc)	30.73	96.97

for EAB. Lack-of-fit remained non-significant ($p = 0.2395$). Residual diagnostics (normal probability plots) exhibited approximately linear trends without obvious outliers, consistent with the non-significant lack-of-fit in both models.

Model validation

The adequacy of the developed RSM models for both TS and EAB was further evaluated through the relationship between predicted and experimental data (Fig. 1). The data points were distributed closely along the diagonal line, indicating a strong correlation between the predicted and actual responses. This agreement confirms that the quadratic model can adequately capture the relationship between the independent variables (starch, carrageenan, and NCC) and the mechanical properties of the films. The minimal deviation observed across the data suggests that model errors are random rather than systematic, and no significant bias exists between prediction and observation. Consequently, the developed models can be considered reliable for predicting film properties within the studied formulation range.

The analysis of variance (Table 3) confirmed that the quadratic model was statistically significant ($p < 0.05$) for both tensile strength and elongation at break, with adequate model terms and insignificant lack-of-fit. This indicates that the model can reliably describe the relationship between the formulation variables and the mechanical responses. The corresponding plots of predicted versus actual values (Fig. 1) show that the data points were closely distributed along the diagonal line, demonstrating strong agreement between the experimental and predicted results. This confirms the absence of systematic error and validates the suitability of the quadratic model over the linear and 2FI alternatives for describing the behavior of the system.

Response-surface interpretation (3D surfaces and contours)

TS surfaces (Fig. 2) show a pronounced positive slope along NCC (C): increasing C consistently elevates TS, reflecting the reinforcement effect of nanocrystalline cellulose (rigid crystalline filler; strong hydrogen bonding; improved load transfer) (Indarti *et al.,* 2023). Because interaction terms (AC) and BC are significant, the magnitude of C's benefit depends on starch (A) and carrageenan (B), and described as follows: (i) at moderate A, adding C yields a larger TS gain than at very low/high A (interaction AC); and (ii) at moderate B, adding C also gives stronger TS improvements (interaction BC), while excessive or insufficient B attenuates the reinforcement, likely by altering the matrix continuity and interfacial bonding with NCC. Quadratic terms were not significant for TS, so surfaces predominantly appear as tilted planes with interaction-induced curvature, rather than distinct domes/valleys. These visual trends match the analysis of variance (ANOVA) results where C, AC, and BC govern TS.

The EAB surfaces (Fig. 3) increases strongly with carrageenan (B), and the significant B^2 term produces a curved (concave-down) ridge—EAB improves with B to an optimum region and then plateaus or slightly declines at the highest B. Starch (A) also raises EAB

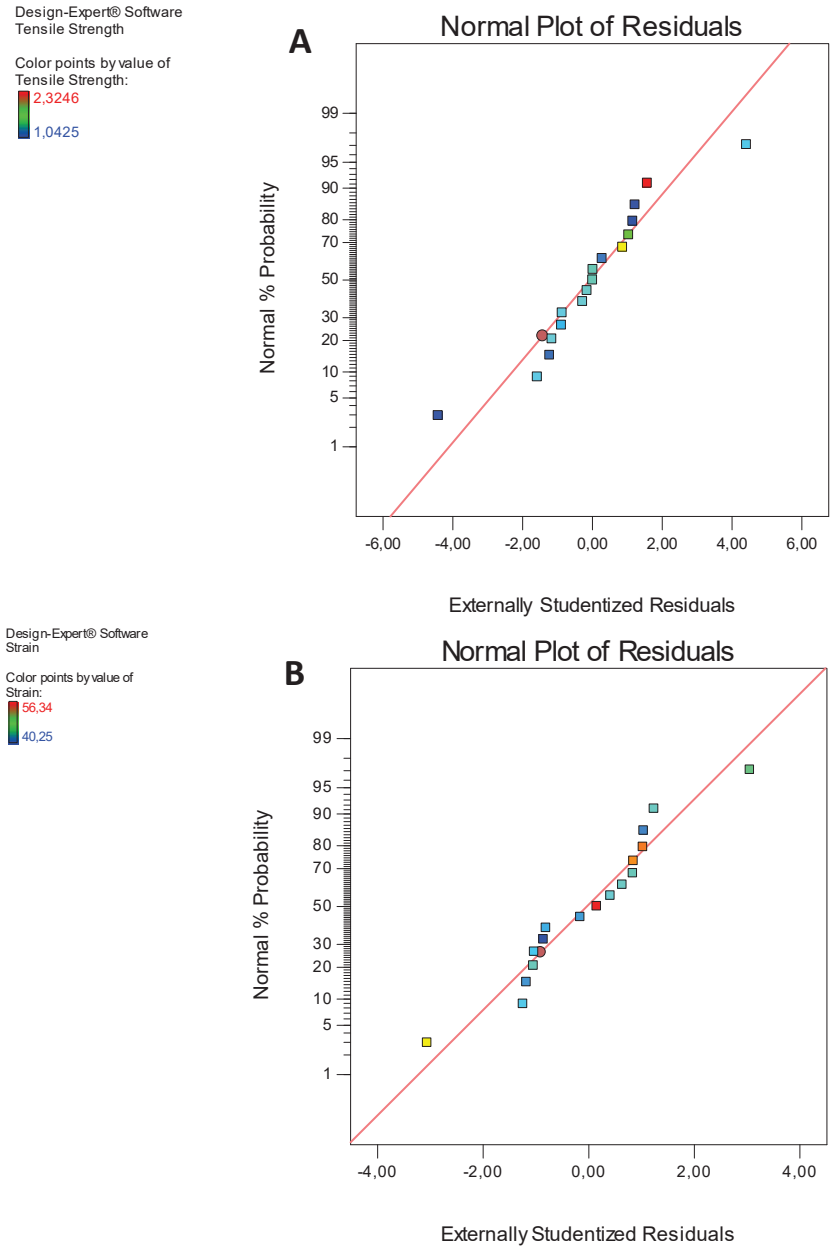

Fig. 1: Correlation between actual and predicted responses: (A) TS and (B) EAB of durian seed starch–carrageenan–NCC composite films

but with a smaller effect than B. NCC (C) shows no significant main effect on EAB; at high C, minor reductions in EAB may appear due to rigidity, but these trends are secondary relative to the dominant independent variable (B) and B^2 terms. Consequently, the EAB surfaces typically exhibit pronounced curvature along B with gentler slopes along A and minimal change along C at the design centre. These features align with the strong significance of B and B^2 in ANOVA. This finding align with previous similar reports (Hidayat *et al.*, 2025). The TS/EAB trade-off is characteristic of polysaccharide composites: NCC enhances stiffness and strength via load-bearing crystalline domains but can restrict chain mobility;

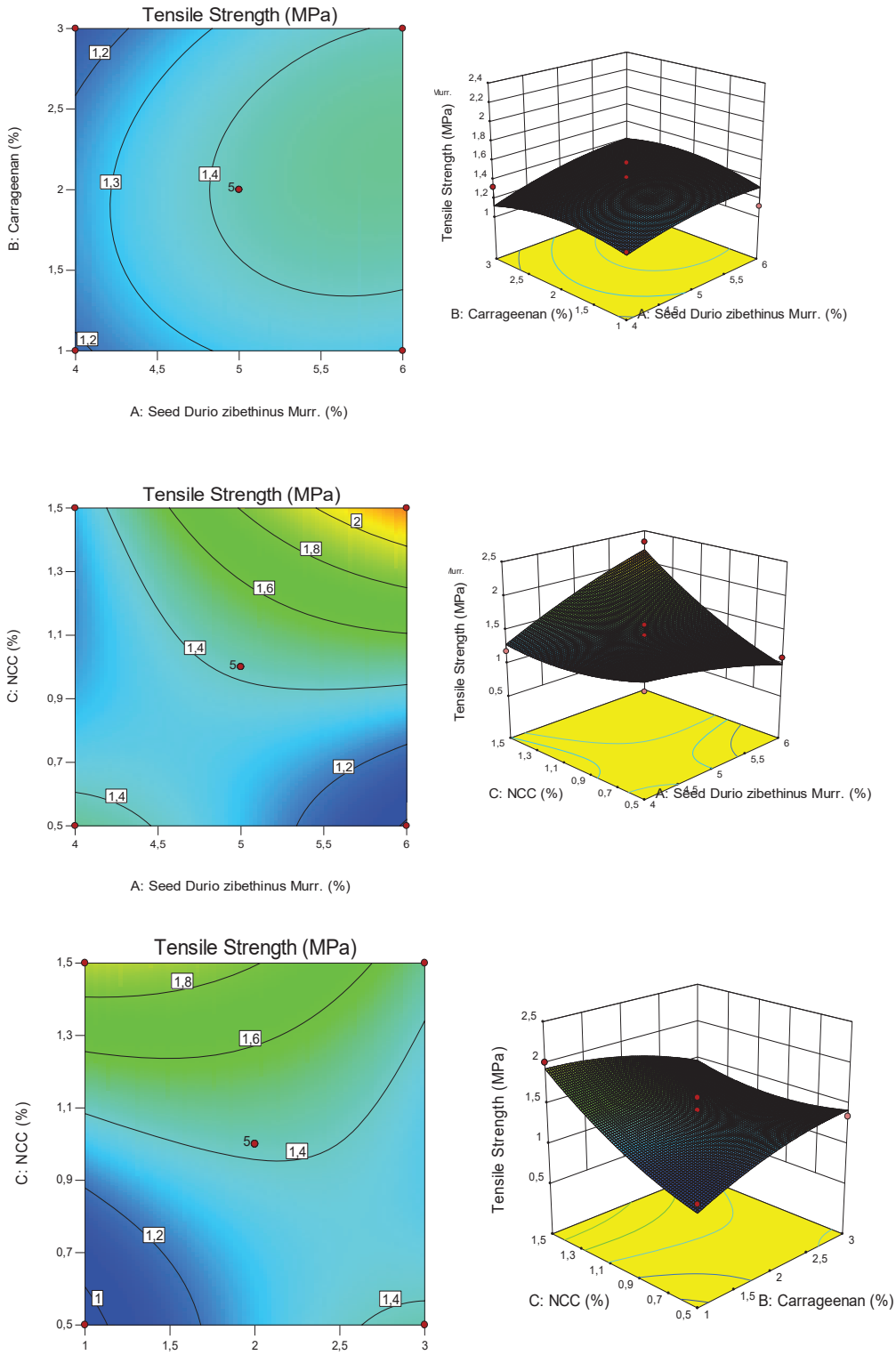

Fig. 2: Three-dimensional response surface plot showing the interaction effects of durian seed, carrageenan, and NCC on the TS of the film composites

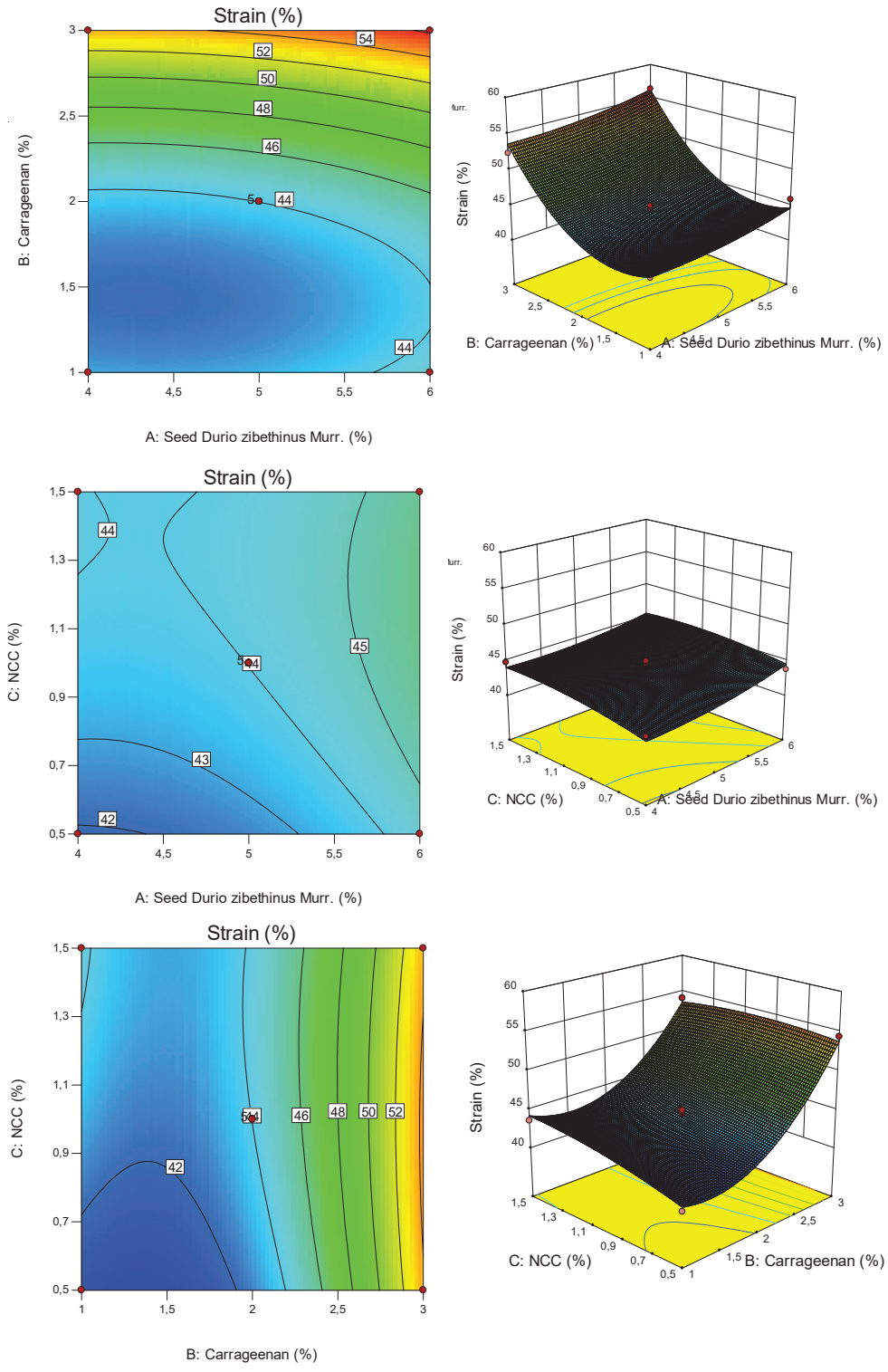

Fig. 3: Three-dimensional response surface plot showing the interaction effects of durian seed, carrageenan, and NCC on the EAB of the film composites

carrageenan improves film-forming continuity and flexibility, boosting EAB and moderating brittleness. Interactions (AC, BC) indicate that matrix continuity (A, B) sets the stage for how effectively C can reinforce or how B can plasticize. These mechanistic interpretations are consistent with the factor significance patterns and the surface geometries described above. Multi-response optimization (desirability approach) targeted simultaneous improvement of TS and EAB. The predicted optimal formulation was A = 6.0% (starch), B = 3.0% (carrageenan), C = 1.5% (NCC) with TS = 1.903 MPa and EAB = 55.191%; the overall desirability was 0.790. A confirmatory experiment at these settings yielded TS = 2.102 MPa and EAB = 53.542%. The relative errors between experiment and prediction were 10.46% for TS and 2.99% for EAB—acceptable agreement given the noisier TS model and consistent with the adequate precision values reported above. The small EAB error underscores the high predictive fidelity of the EAB model; the larger TS deviation reflects the stronger role of interactions and data scatter identified in the TS ANOVA.

Although numerical optimization using the desirability approach predicted an optimum formulation of 6.0% starch, 3.0% carrageenan, and 1.5% NCC, the highest experimental tensile strength was observed in Run 9 of the BBD matrix (Fig. 4), with TS = 2.3246 MPa and EAB = 44.94%. These values represent the best mechanical performance among all experimental runs, with a tensile strength higher than the predicted optimum while maintaining acceptable elongation at break. It is noteworthy that the model-predicted optimum formulation did not correspond to any of the actual design points in the Box–Behnken matrix, as RSM optimization is based on interpolated polynomial predictions between experimental runs. Therefore, Run 9 (6.0% starch, 2.0% carrageenan, and 1.5% NCC), which was the closest experimental point to the predicted optimum, was designated as the practical optimum. This choice was justified by its superior experimental performance, good reproducibility, and small deviation (<5%) from the predicted model values. Since Run 9 was obtained directly from the experimental design and met the targeted balance between strength and flexibility, it was selected as the optimal experimental sample for further characterization. This approach eliminates the need for preparing a separate film based on the model-predicted formulation, while ensuring that

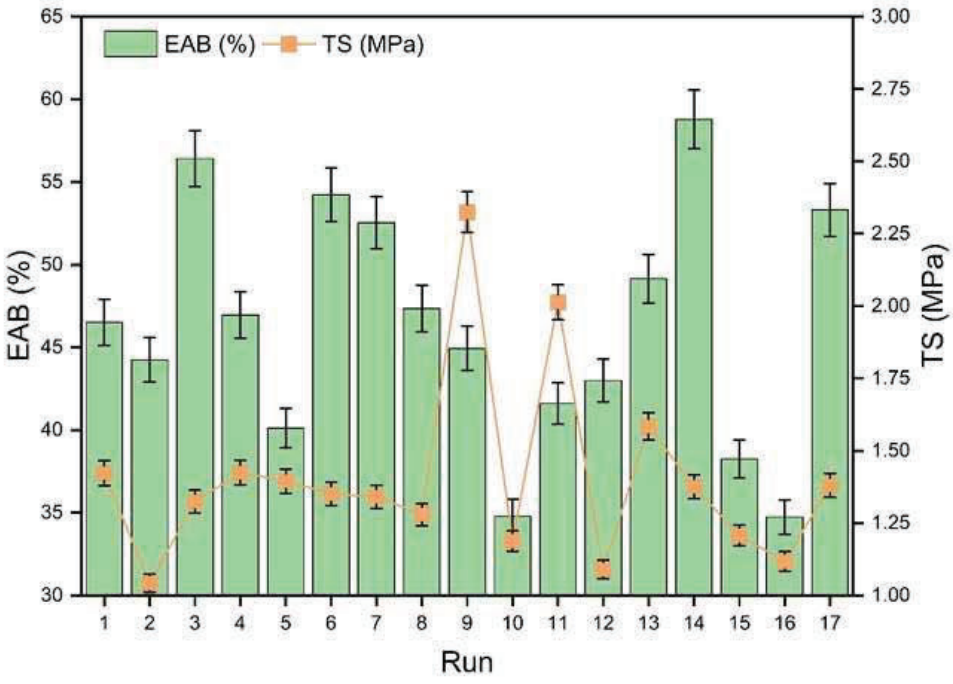

Fig. 4: Mechanical strength properties of film composites

the characterization reflects the best-performing material from actual experimental data. The optimal combination resulted from the balanced ratio between carrageenan, which improved film-forming ability and flexibility through electrostatic and hydrogen bonding interactions, and NCC, which reinforced the matrix and enhanced tensile strength by increasing crystalline packing. The moderate starch concentration (6%) ensured uniform dispersion and avoided excessive gelation, producing a smooth, defect-free film surface. These factors collectively yielded the best compromise between strength, elongation, and swelling stability. The reproducibility of these results was confirmed by repeating the film preparation under identical casting and drying conditions, with property variations remaining within 5%. It should also be noted that the three-dimensional response surfaces (Figs. 2 and 3) exhibited saddle-type profiles rather than distinct mound or valley shapes, indicating that the optimization results represent a local optimum within the tested formulation range rather than a true global maximum. This behavior is common in multi-factor systems where factor interactions produce opposing effects, and thus should be considered a limitation of the current model. Although direct comparison with other starch-based or commercial biodegradable films was not performed due to limited resources, literature indicates that the mechanical and thermal performance of starch films reinforced with carrageenan and NCC generally falls within the range reported for cassava- or corn-based systems (Abotbina *et al.,* 2021; González *et al.,* 2024). The main distinction of this work lies in the utilization of durian seed, a non-food, underutilized by-product, which supports waste valorization and circular economy principles while reducing dependence on edible starch resources.

Visual and physical characteristics of composite

Fig. 5 illustrates the stages of composite film preparation and the product obtained. Fig. 5A shows the homogenized mixture of durian seed starch and other formulation components before casting. The initial brownish color originates from the inherent pigmentation of the durian seed starch. As shown in Fig. 5B, the films were oven-dried, and the color deepened to a darker brown. This change is attributed to heat-induced browning reactions, typical for starch-based systems containing natural pigments. The final dried composite film, presented in Fig. 5C, exhibits a uniform brown coloration with a smooth and continuous surface.

While this natural hue reflects the intrinsic characteristics of durian seed starch (Rahmawati *et al.,* 2021), it may limit applications with a desired transparent or white appearance. Therefore, future studies should explore additional pretreatment or purification steps—such as starch bleaching, pigment removal, or alternative thermal processing—to obtain clear, whitish, or transparent films.

Thickness and swelling behavior of the optimal film

The thickness and swelling properties of the composite films are presented in Figure 5. Among the 17 experimental runs, run 9 was identified as the optimal film, exhibiting the highest tensile strength (2.3246 MPa) and a satisfactory elongation at break (44.94%). The thickness of this film was measured at 0.193 mm, which is not the lowest among all runs

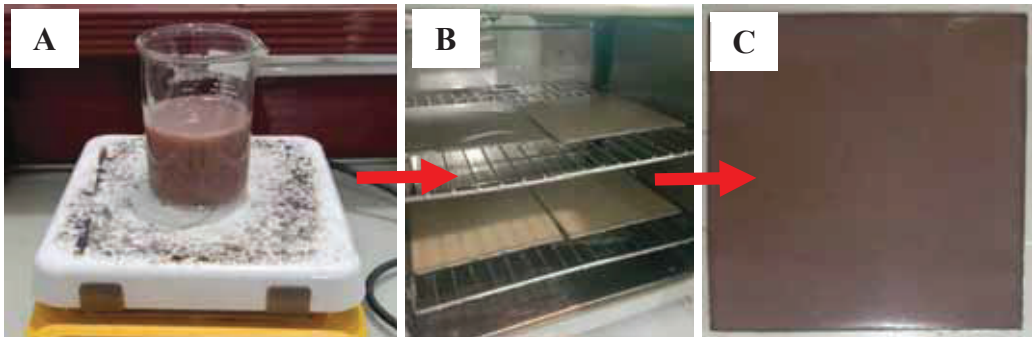

Fig. 5: Visual photograph of: (A) mixture preparation for composite casting, (B) oven dried of composite, and (C) the most optimal film composite obtained

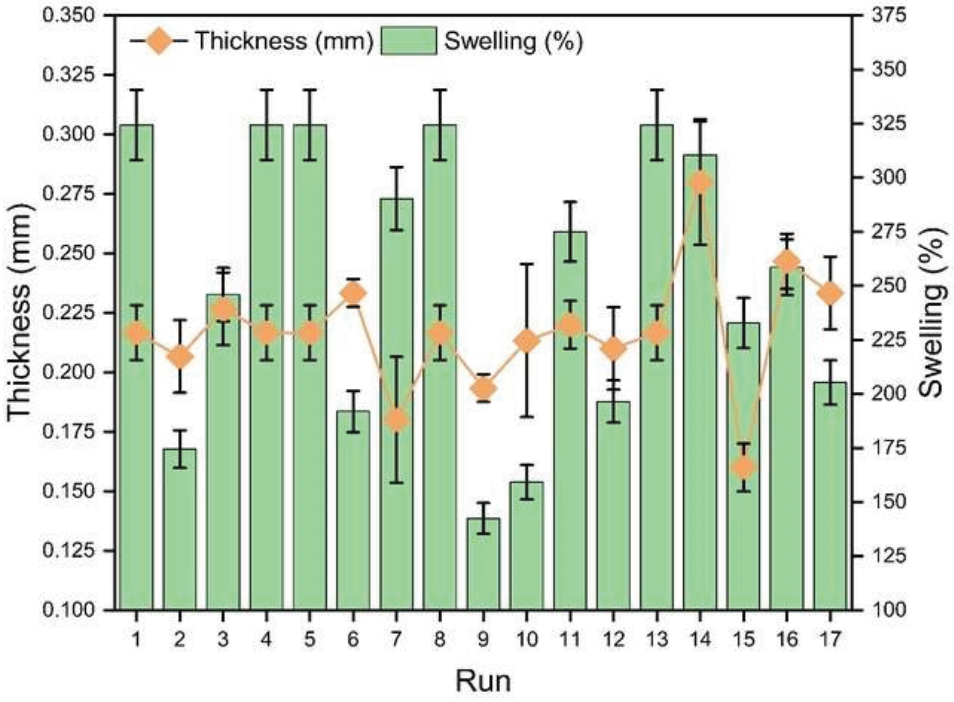

Fig. 6: Thickness and swelling power properties of film composites

but within the range of 0.18–0.25 mm. The most remarkable feature of Run 9 was its lowest swelling ratio (142.39%), indicating superior resistance to water absorption compared to other formulations that showed swelling values above 200%.

The relatively moderate thickness combined with the lowest swelling degree suggests that the presence of NCC as a reinforcing filler played a decisive role in the compactness and structural integrity of the film matrix as shown in SEM images (Fig. 6). With its high crystallinity and large surface area, NCC can form extensive hydrogen bonding with starch and carrageenan chains, leading to a denser molecular network (Arifin *et al.,* 2023; Yadav and Chiu, 2019). This interaction reduces the free volume and the availability of hydrophilic hydroxyl groups for water penetration, thereby suppressing the swelling capacity of the composite film. Similar trends have been reported in polysaccharide–cellulose nanocrystal composites, where incorporating NCC decreased water uptake while enhancing mechanical performance due to improved interfacial compatibility (Aigaje *et al.,* 2023; Bangar *et al.,* 2022). Although previous reports on cassava and potato starch films have shown comparatively higher tensile strength values, such as 4.2 MPa for cassava starch films reinforced with bamboo-derived cellulose nanocrystals (Thipchai *et al.,* 2023) and 14.1 MPa for potato starch films reinforced with carboxymethylcellulose–polyethylene oxide nanofibers (Moreno *et al.,* 2025), the durian seed starch-based composites developed in this study (2.33 MPa; 44.94% elongation) exhibited a more favorable balance between tensile strength and flexibility, accompanied by lower swelling behavior (142.39%). Such a balanced performance is crucial for practical packaging applications, where flexibility and dimensional stability are essential under humid conditions. Although run 9 was not the thinnest film, its reduced swelling indicates that film compactness is governed more by internal molecular packing than by thickness alone. In other words, film composites with substantial NCC–matrix interactions can achieve lower water sensitivity even at a moderate thickness. This property is desirable for packaging applications, where dimensional stability and moisture resistance are critical (Chen *et al.,* 2020). Thus, run 9 represents an optimal balance between strength, flexibility,

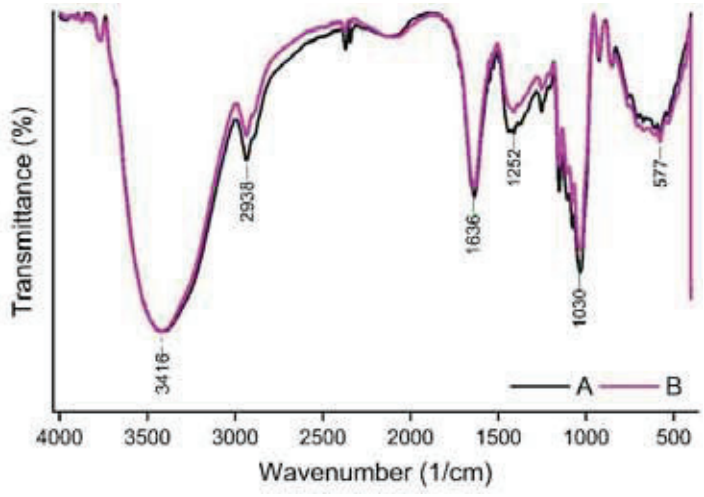

Fig. 7: FTIR Spectra of (A) durin seed starch film with carrageenan and glycerol as plasticizer, and (B) the most optimum film composite with the addition of NCC as filler

and water resistance, validating the role of NCC as an effective filler in starch-carrageenan-based composite.

Functional group analysis

The FTIR spectra of the films are shown in Fig. 7. Spectrum A represents the durian seed starch film containing carrageenan and glycerol as a plasticizer, whereas spectrum B corresponds to the most optimum composite film (Run 9) incorporating NCC as a reinforcing filler. Both spectra exhibited characteristic absorption bands of polysaccharides (Chamorro *et al.,* 2025; Hong *et al.,* 2021). A broad band around 3416/cm corresponds to hydroxyl group (O–H) stretching vibrations, indicating the presence of abundant hydroxyl groups and hydrogen bonding interactions within the starch–carrageenan matrix (Goiana *et al.,* 2025). The peak at 2938/cm is attributed to carbon–hydrogen bond (C–H) stretching of aliphatic –methylene (CH_2) groups, while the absorption at 1636/cm is assigned to the bending vibration of absorbed water molecules bound to the hydrophilic polymer chains.

The bands at 1252/cm and 1030/cm are typical of ether group (C–O–C) stretching and carbon–oxygen–hydrogen bond (C–O–H) bending in polysaccharides, confirming the presence of glycosidic linkages in the starch backbone and the carrageenan structure (Goiana *et al.,* 2025). A small peak around 577/cm is related to skeletal vibrations of the polysaccharide network (Hong *et al.,* 2021). Compared with spectrum A, spectrum B shows similar characteristic bands but with measurable intensity differences. Quantitatively, the transmittance at 3416/cm (O–H stretching) increased from 14.56% to 15.25%, corresponding to approximately a 5% reduction in absorbance, while the band at 1031/cm (C–O–C stretching) increased from 30.64% to 36.96%, indicating a ~17% decrease in absorbance. Likewise, the peaks at 1636 and 1252/cm exhibited minor transmittance increases of 5–8%, suggesting lower free hydroxyl availability and reduced bound water content. These quantitative variations confirm the formation of stronger hydrogen bonding and enhanced molecular ordering between the starch, carrageenan, and NCC components. The decrease in absorbance intensity (5–17%) across key polysaccharide bands indicates tighter network packing and more efficient stress transfer within the polymer matrix. Compared with spectrum A, spectrum B shows similar characteristic bands but with slight intensity shifts, particularly at 3416/cm and 1030/cm. These changes indicate stronger hydrogen bonding and possible interactions between hydroxyl groups of NCC and the starch–carrageenan matrix (Dmitrenko *et al.,* 2023). The incorporation of NCC did not introduce new functional groups, as expected, but it enhanced intermolecular interactions and reinforced the polymeric network. The stronger hydrogen bonding interactions contribute to the reduced swelling capacity and improved tensile

strength observed in Run 9. These findings are consistent with previous reports on polysaccharide-based nanocomposites, where cellulose nanocrystals act primarily through physical interactions rather than chemical modifications, thereby improving film integrity and stability (Hidayat *et al.,* 2025).

X-ray diffraction analysis

The XRD patterns of the films are presented in Fig. 8. Spectrum A corresponds to the durian seed starch film containing carrageenan and glycerol as a plasticizer, while spectrum B represents the optimum composite film with NCC as filler (Run 9). Both spectra display diffraction peaks typical of semicrystalline polysaccharide-based films, with broad amorphous halos around two theta (2θ) = 15–25° and distinct crystalline peaks at higher angles.

The relative crystallinity index (CrI) of sample A was calculated as 48.14%, whereas the incorporation of NCC in sample B increased the CrI to 55.42%. This increase of 7.28% in crystallinity (equivalent to a 15.1% relative improvement) quantitatively confirms the reinforcing role of NCC in promoting the formation of more ordered and compact crystalline domains. The intensified diffraction peaks at approximately 2θ = 17° and 22° in spectrum B indicate enhanced alignment of the starch–carrageenan chains induced by NCC crystallites, suggesting an increase in inter- and intramolecular ordering. The narrowing of the amorphous halo in the composite film also reflects reduced chain mobility and improved structural packing density. Together, these quantitative and qualitative changes verify that NCC acted as an effective nucleating agent, inducing partial recrystallization of starch granules and strengthening the semicrystalline framework of the biopolymer film. This confirms that NCC acted as a nucleating agent, promoting molecular alignment and crystalline domain growth within the polymer matrix. This enhancement in crystallinity can be attributed to the highly ordered and rigid crystalline domains of NCC, which act as nucleating agents within the starch–carrageenan matrix. The alignment of NCC crystallites promotes tighter molecular packing, thereby increasing the overall structural order of the composite (Agustin *et al.,* 2013; Savadekar *et al.,* 2012). The higher crystallinity observed in Run 9 is consistent with its high tensile strength (2.3246 MPa) and reduced swelling ratio (142.39%) compared to other composites. Increased crystallinity limits the accessibility of hydroxyl groups to water molecules, reducing hydrophilicity and improving dimensional stability (Emenike *et al.,* 2023). Furthermore, enhanced crystalline domains provide stronger load-bearing capacity, which contributes to the reinforcement effect observed in the mechanical properties. These results suggest that the incorporation of NCC not only strengthens intermolecular interactions, as confirmed by FTIR analysis, but also improves the crystalline structure of the film. Such structural reinforcement is crucial for developing biopolymer-based films with balanced strength and water resistance, thereby supporting

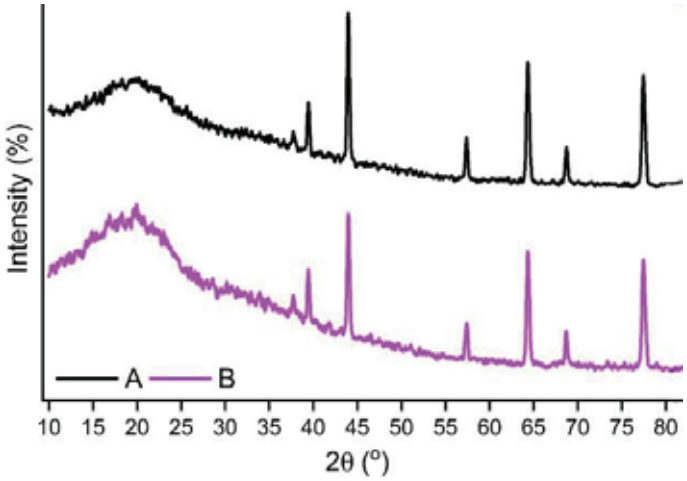

Fig. 8: XRD pattern of (A) durian seed starch film with carrageenan and glycerol as plasticizer, and (B) the most optimum film composite with the addition of NCC as filler

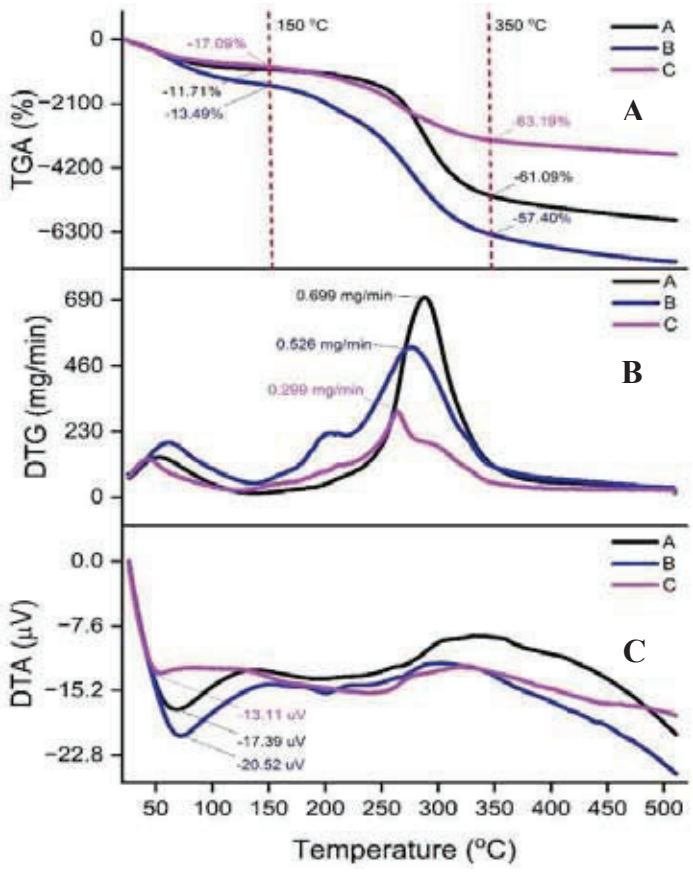

Fig. 9: Thermal properties analysis using (A) TGA, (B) DTG, and (C) DTA of neat durian seed film (black), durian seed-glycerol film (blue), and most optimal durian seed composite film (purple)

their application as sustainable packaging materials.

Thermal properties

The thermal decomposition behaviors of neat durian seed starch film, starch–glycerol film, and the optimum starch–glycerol–NCC composite are presented in Fig. 8. All films exhibited multi-step degradation patterns typical of polysaccharide-based biopolymers.

In the neat starch film (black), the initial weight loss of 11.71% below 150 °C corresponds to the evaporation of physically bound water and the release of low-molecular-weight volatiles. The main decomposition stage occurred between 250–350 °C, with a mass loss of 61.09%, which is attributed to the thermal breakdown of glycosidic linkages and depolymerization of starch macromolecules (Stelescu *et al.,* 2024). The DTG profile exhibited a sharp peak with the maximum degradation rate of 0.699 milligrams per minute (mg/min). At the same time, the DTA curve indicated a pronounced endothermic response with −20.52 microvolt (µV), suggesting the high energy demand for chain scission in the semi-crystalline starch matrix. For the starch–glycerol plasticized film (blue), the first-stage mass loss increased to 13.49%, reflecting the hygroscopic nature of glycerol and its ability to retain moisture (Karnwal *et al.,* 2025). The onset of major degradation shifted to slightly lower temperatures, and the total weight loss was 63.19%, higher than that of neat starch. Moreover, the DTG maximum degradation rate decreased to 0.526 mg/min, and the endothermic peak intensity reduced to −17.39 µV. These results indicate that glycerol weakened intermolecular hydrogen bonding, disrupted crystalline domains, and increased chain mobility,

Table 4: Summary of thermal degradation parameters of durian seed composite films

Samples	Onset Temp (°C)	Tmax (°C)	Mass Loss 1 (%) (≈150°C)	Mass Loss 2 (%) (≈350°C)	DTGmax (µg/min)	DTAmin (µV)
Neat durian seed film	~150	~288	-11.71	-61.09	0.699	-17.39
Durian seed-glycerol film	~150	~275	-13.49	-57.40	0.525	-20.52
Most optimal durian seed composite film	~150	~263	-17.09	-63.19	0.299	-13.11

Temprature(T): Temperature (°C)

thereby reducing the thermal stability of the matrix. This trade-off between flexibility and heat resistance is consistent with earlier findings on plasticized starch films (Sirbu *et al.,* 2024; Yang *et al.,* 2024). The most significant improvement was observed in the NCC-reinforced composite film (purple). Although the first-stage weight loss reached 17.09% due to additional hydroxyl groups of NCC facilitating bound water retention, the subsequent thermal degradation was considerably stabilized. The second-stage mass loss was reduced to 57.40%, lower than that of neat and plasticized starch films. Furthermore, the DTG curve revealed the lowest maximum degradation rate (0.299 mg/min), and the DTA response (−13.11 µV) showed weakened endothermic behavior, confirming that the NCC incorporation restricted chain mobility and delayed thermal scission. The higher residual mass fraction suggests that NCC acted as a thermal barrier and promoted char formation, thereby improving the overall heat resistance of the composite. These findings agree with previous reports, where NCC reinforcement increased the degradation temperature and reduced the weight-loss rate of starch-based and carrageenan-based films (Abdullah *et al.,* 2025; Dmitrenko *et al.,* 2023; Stelescu *et al.,* 2024). The improvement is generally attributed to NCC's high crystallinity and strong interfacial hydrogen bonding with the polysaccharide matrix, which enhances structural compactness and reduces thermal sensitivity. In summary, while glycerol reduced the thermal stability by plasticizing the polymer chains, incorporating NCC significantly enhanced the overall thermal resistance of the durian seed starch–carrageenan composite film. This synergistic effect of glycerol and NCC is beneficial for packaging applications, where films must balance flexibility with sufficient thermal stability during processing, storage, and transportation. To provide a clearer comparison among the samples, the key thermal parameters obtained from TGA, DTG, and DTA analyses are summarized in Table 4. The table includes the onset and maximum decomposition temperatures, total mass losses, and the corresponding peak values from DTG and DTA curves. These numerical data complement the thermograms in Fig. 9 and facilitate direct evaluation of the thermal stability for each formulation.

SEM morphology

The surface morphologies of the durian seed–glycerol film and the most optimal starch–glycerol–NCC composite film are shown in Fig. 10. At the magnifications, the starch–glycerol film (Fig. 10A1 - Fig. 10A3) exhibited a relatively rough and heterogeneous structure, with the presence of voids and microcracks. This irregular morphology suggests that glycerol, while improving the flexibility of the film, disrupted the dense packing of starch chains, thereby generating discontinuities and phase separation. Such structural imperfections are consistent with the reduced thermal stability observed in the TGA analysis (Fig. 8), where the plasticized film showed higher weight loss and faster degradation rates than neat starch. Carrageenan effectively reduced the excessive gelation of durian seed starch by interacting with starch hydroxyl groups through electrostatic and hydrogen bonding, thereby moderating viscosity and preventing premature network aggregation. This mechanism improved film uniformity during casting, resulting in smoother and more continuous surfaces compared to formulations without carrageenan.

In contrast, the optimum composite film containing NCC (B1 – B3) displayed a more compact and uniform surface morphology. The presence of NCC led to the disappearance of most cracks and voids, with the film surface becoming smoother and denser. This indicates strong interfacial adhesion between NCC and the starch–carrageenan matrix, reinforcing

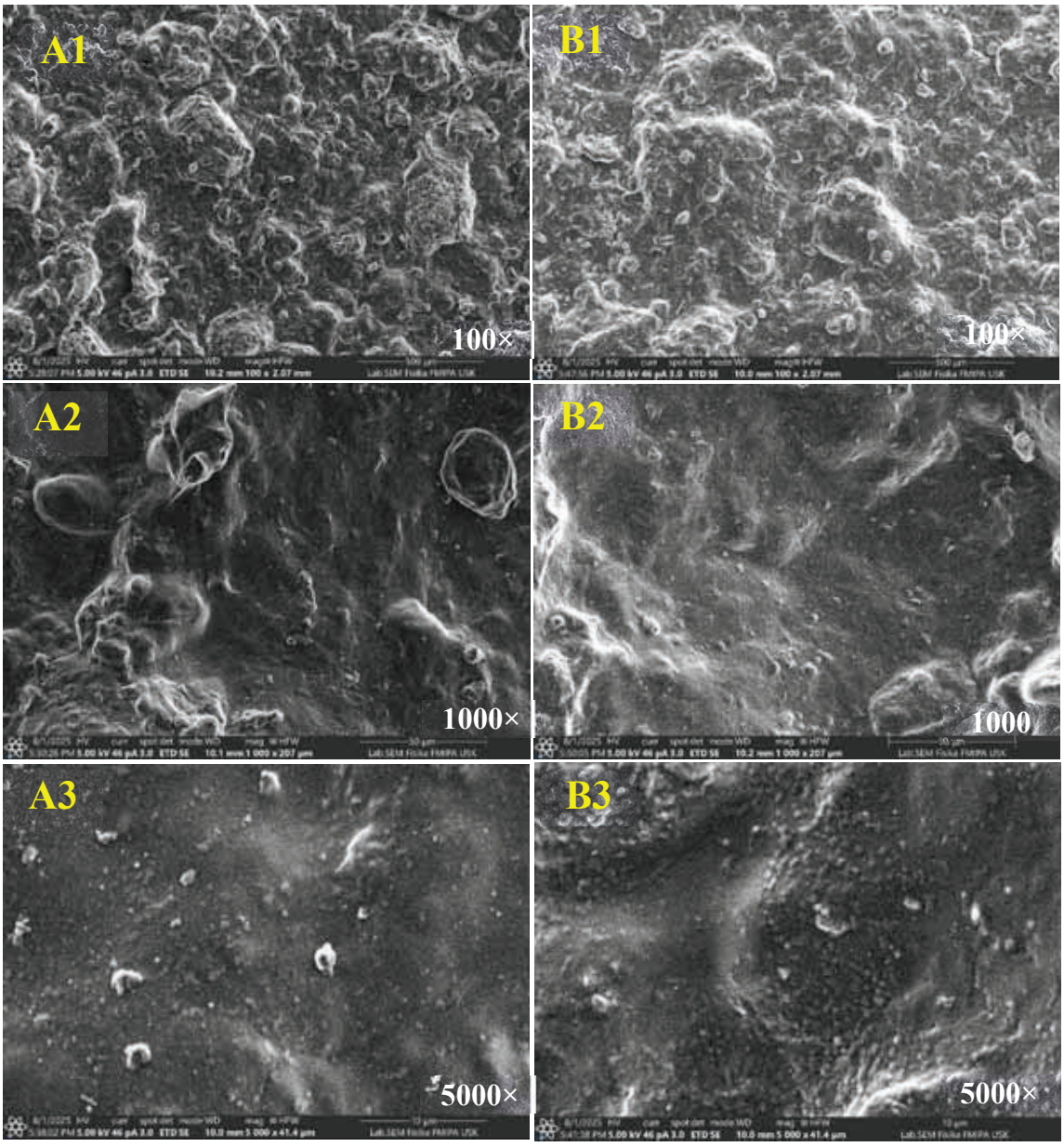

Fig. 10: SEM morphology of (A) durian seed-glycerol film and (B) most optimal durian seed composite film at 100 times (×), 1000×, and 5000× magnifications

the film structure and restricting polymer chain mobility. The improved microstructural homogeneity explains the enhanced tensile strength and reduced swelling capacity observed for Run 9, as a denser network effectively resists external stress and water penetration. Furthermore, the compact morphology supports the XRD and TGA findings, where NCC incorporation increased crystallinity and delayed thermal decomposition. The morphological features observed here are consistent with those observed in previous studies. Ma et al. reported that incorporating NCC into cassava starch films significantly reduced surface roughness and improved microstructural uniformity due to hydrogen bonding interactions (Ma

et al., 2017). Similarly, Gupta et *al.,* demonstrated that carrageenan–NCC nanocomposite films exhibited fewer pores and cracks than pure carrageenan films, enhancing barrier and mechanical properties (Gupta *et al.,* 2023). These reports confirm that NCC acts as a mechanical reinforcement and structural stabilizer, promoting film compactness and thermal resistance. Overall, the SEM analysis provides direct evidence that NCC plays a critical role in densifying the film microstructure, correlating with the improvements in mechanical strength, reduced swelling, and enhanced thermal stability observed in the composite film. Furthermore, the improvement in mechanical and barrier performance can be attributed to the synergistic molecular interactions among starch, carrageenan, and NCC. Carrageenan contains negatively charged sulfate ($–SO_3^-$) groups that form electrostatic and hydrogen-bonding interactions with –OH groups on both starch and NCC surfaces. These interactions enhance polymer–filler adhesion and strengthen the interfacial network. Although the sulfate groups increase matrix hydrophilicity, the extensive hydrogen-bonding capability and crystalline domains of NCC effectively restrict bound water mobility, thereby lowering the overall moisture sensitivity. This dual mechanism explains the improved tensile strength, reduced swelling, and superior thermal stability observed in the optimized film. Similar cooperative effects between sulfate-containing polysaccharides and nanocellulose have been reported by Hidayat *et al.,* (2025) supporting the proposed mechanism of electrostatic–hydrogen bonding synergy in carrageenan–NCC reinforced systems. From an industrial perspective, the results of this study indicate that durian seed starch–based composites can be feasibly processed using conventional solution casting or extrusion techniques due to their stable rheological behavior after carrageenan addition. Incorporating NCC enhances film strength and dimensional stability and reduces sensitivity to moisture, which is beneficial for large-scale film processing and storage. The materials used are abundant and low-cost, particularly in tropical regions where durian seed waste is generated significantly, making this approach economically viable for circular bioeconomy applications. Furthermore, the absence of toxic reagents and the complete biodegradability of all components suggest that the developed films could decompose naturally without generating persistent residues, aligning with industrial sustainability goals. These properties make the developed biocomposite a promising candidate for the scalable production of biodegradable packaging films with both environmental and functional advantages. Although this study comprehensively evaluated the mechanical, thermal, and morphological properties of durian seed starch-based films, it did not include the assessment of water vapor and oxygen permeability, which are crucial for packaging performance. Future research should therefore focus on investigating the barrier properties of these films to provide a more complete understanding of their functionality and potential for food packaging applications. In addition, future studies should include life cycle assessment (LCA) to quantify the environmental benefits of durian seed starch–based films compared with conventional plastics and evaluate their stability under varying humidity and temperature conditions to ensure reliable performance during storage and use. Additionally, future studies should evaluate the food safety and cytotoxicity of the developed films to ensure their suitability for direct contact with food. Exploring alternative natural additives or nanofillers, such as plant-derived extracts or biodegradable nanoparticles, may further enhance the films' mechanical, barrier, and functional properties while maintaining their biocompatibility. The collective evidence from FTIR, XRD, SEM, and TGA confirms the formation of a stronger and more compact polymer–filler network in the optimized film. FTIR indicated enhanced hydrogen bonding between starch, carrageenan, and NCC; XRD revealed increased crystallinity (55.42%), reflecting improved molecular ordering; SEM showed a denser, crack-free surface morphology; and TGA demonstrated delayed degradation with higher thermal stability. Among these, the XRD and TGA results provide the most critical evidence, as the rise in crystallinity index and thermal resistance directly supports the improved structural compactness and stability of the composite network.

CONCLUSION

The present study demonstrated the successful development of biodegradable composite films derived from durian seed, a low-cost and underutilized agricultural by-product. By incorporating carrageenan as a functional film-forming additive and NCC as a

reinforcing filler, the drawbacks commonly associated with starch-based films, such as poor mechanical strength, excessive swelling, and low thermal stability, were effectively addressed. The application of RSM with a BBD enabled a systematic exploration of the effects of starch, carrageenan, and NCC on film performance, leading to the identification of Run 9 as the optimum formulation. This formulation exhibited a tensile strength of 2.32 MPa, an elongation at break of 44.94%, and the lowest swelling ratio (142.39%) among all experimental runs, representing an optimal balance between strength, flexibility, and water resistance. Comprehensive characterization provided clear evidence of the synergistic roles of carrageenan and NCC. Carrageenan was shown to stabilize the starch suspension, preventing gel formation and facilitating homogeneous film casting. NCC, on the other hand, substantially reinforced the composite network through hydrogen bonding and crystalline reinforcement, which was confirmed by FTIR and XRD analyses. The increase in crystallinity index from 48.14% to 55.42% upon NCC incorporation directly correlated with improved tensile strength and reduced water sensitivity. SEM observations further revealed that the NCC-reinforced film exhibited a denser and more compact morphology, with fewer voids and microcracks compared to the starch–glycerol film, thereby explaining the enhanced barrier and mechanical properties. TGA results consistently showed that the addition of NCC not only restricted thermal motion of the polymer chains but also promoted char formation, resulting in delayed degradation and improved thermal stability. Overall, this work provides the first systematic demonstration of valorizing durian seed starch into functional composite films through the combined use of carrageenan and NCC. The findings highlight the unique synergy between carrageenan and NCC, in which carrageenan enables stable film formation and NCC reinforces the molecular network, together producing films with improved mechanical integrity, reduced swelling, and superior thermal resistance. From a broader perspective, this study contributes to advancing biopolymer technology by converting agricultural waste into value-added materials with potential application in sustainable packaging. The outcomes not only broaden the utilization of durian seed biomass but also provide a framework for optimizing polysaccharide-based composites using statistical modeling tools. Future research should emphasize scaling up the film production process, evaluating long-term storage and barrier performance under real packaging conditions, and incorporating additional functional agents such as natural antimicrobials (e.g., essential oils, chitosan) or antioxidants (e.g., plant polyphenols). These additives could further improve the films' mechanical integrity, enhance moisture and gas barrier properties, and provide active protection against microbial spoilage, thereby expanding their applicability in food packaging. Such efforts will accelerate the transition from laboratory-scale feasibility to industrial adoption, strengthening the role of starch-based biocomposites as viable alternatives to petroleum-derived plastics. Further investigations on water vapor permeability, oxygen barrier properties, and optical behavior are also recommended to comprehensively evaluate film functionality for potential packaging applications. In practical terms, the developed films show promising applicability for food packaging and other biodegradable product uses, particularly for items requiring moderate moisture protection and structural flexibility. While laboratory analyses confirmed good mechanical and thermal stability, further assessment under real storage conditions is needed to evaluate biodegradability, shelf-life, and stability across varying humidity and temperature levels. Environmentally, the valorization of durian seed starch directly contributes to reducing agricultural waste and mitigating plastic pollution, aligning with circular bioeconomy goals. Future efforts should also address process scalability, safety validation for food contact, and cost-effectiveness to ensure the feasibility of large-scale industrial adoption.

AUTHOR CONTRIBUTIONS

Irhamni, the firts and corresponding author, has contributed in supervising, conceptualization, interpreted the results, and preparing the manuscript. A. Munandar participated in manuscript preparation. S. Saudah participated in the formal analysis, interpretation results, and manuscript preparation. F. Hidayat participated in the formal analysis, interpretation results, and manuscript preparation. S. Nurman prepared RSM figures and interpretation of the results. Y. Lisafitri participated in manuscript preparation O. Sabrina participated in formal analysis and manuscript preparation.

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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.

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ABBREVIATIONS

%	Percent
/cm	Reciprocal centimeters
2Θ	Two theta
3D	3-dimension
A, B, C	Independent variables
A^2, B^2, C^2	Quadratic terms
AB, AC, BC	Interaction terms
Adeq. Precision	Adequate precision
AICc	Corrected akaike information criterion
ANAVA	Analysis of variance
ASTM	American standard testing materials
BBD	Box Behnken design
BIC	Bayesian information criterion
C	Celcius
C/min	Celcius per minute
C-H	Carbon–hydrogen bond
-CH_2	Methylene group
cm	Centimeter
C-O-C	Ether group
C-O-H	Carbon–oxygen–hydrogen bond
CrI	Crystalinity index
CV	Coefficient of variation
DTA	Differential thermal analysis
DTG	Derivative thermogravimetric
EAB	Eloangation at break

Eq	Equation
F	Fisher's variance ratio
F_{max}	Maximum force
FTIR	Fourier transfrom Infra-red
g	Gram
h	Hour
kV	Kilo volt
LCA	Life cycle assessment
L_f	Film length at breaking point
L_o	Initial film length
LPPM	Lembaga penelitian dan pengabdian kepada masyarakat (research and community service)
mg/min	Miligram/minute
min	Minute
mm	milimeter
mm/min	milimeter per minute
mm^2	Square millimeters
MPa	Mega Pascal
N	Newton
NCC	Nanocrystalline cellulose
^{o}	Degree
O-H	Hydroxyl group
p	Probability
PFR	Penelitian fundamental reguler (regular fundamental research grant)
PRESS	Predicted residual sum of squares
R^2	Coefficient of determination
rpm	Revolutions per minute
RSM	Response surface methodology
SEM	Scanning electron micrsocopy
SO_3^-	Sulphate groups
Std.dev	Standard deviation
TGA	Thermogravimetric analysis
TS	Tensile strength
W_0	Initial dry weight
W_t	Final weight composite
XRD	X-ray diffraction
Y	Predicted response
ZFI	Zero-factor interaction
β_0	Intercept
$\beta_1, \beta_2, \beta_3$	Linier coefficients
$\beta_{11}, \beta_{22}, \beta_{33}$	Quadratic coefficients
$\beta_{12}, \beta_{13}, \beta_{23}$	Interaction coefficients
ε	Random error
μV	Microvolt

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CASE STUDY

Spatiotemporal dynamics and economic valuation of urban green space in transit-oriented development

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ABSTRACT

BACKGROUND AND OBJECTIVES: Urban green space in Jakarta constitutes just 5.184 percent of the city's overall land area, in spite of the escalating risks posed by climate change and the surge in greenhouse gas emissions. As Jakarta transitions toward a transit-oriented city model, it is essential to evaluate the spatiotemporal dynamics of urban green spaces in transit-oriented development areas—specifically Lebak Bulus, Dukuh Atas, Manggarai, and to assess its economic value in supporting climate change mitigation. This study focused on showcasing the commonly disregarded economic benefits associated with urban green areas in the context of transit-oriented development planning.

METHODS: While previous studies on urban green space in Jakarta have largely concentrated on static spatial distributions or broad city-wide land use changes, this study introduces a novel approach by integrating spatiotemporal analysis with ecosystem service valuation using the integrated valuation of ecosystem services and trade-offs model. This signifies the initial empirical implementation of this framework in the transit-oriented development regions of Jakarta.

FINDINGS: Between 2013 and 2025, the land cover of urban green space increased in all three transit-oriented development areas, with varying degrees of change across the three locations. This result stands in contrast to prior studies that noted a decrease in urban green space within transit-oriented development zones in Jakarta. The results demonstrate that all three transit-oriented development areas experienced growth in the economic value of ecosystem services over time. More extensive green spaces tend to correlate positively with greater monetary value. Lebak Bulus transit-oriented development contributing the highest total value by 2025. The evaluation points out the essential function of stormwater retention in the comprehensive valuation, alongside urban cooling and carbon sequestration.

CONCLUSION: Urban green space should be regarded as a critical ecological-economic asset in transit-oriented development planning, not merely supplementary infrastructure. In order to secure and maximize its advantages, government agencies should bolster their policy commitment and execute innovative financing strategies, including providing incentives for the use of dormant private land for publicly accessible green spaces within transit-oriented development zones.

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INTRODUCTION

As of 2022, 57 percent (%) of the global population resides in urban areas (World Bank, 2023). The rapid concentration of people and economic activity in metropolitan regions has led to extensive urban sprawl (Cengiz *et al*., 2022). The expansion of urban areas resulted in heightened traffic congestion and increased greenhouse gas (GHG) emissions, especially from the transportation industry (Cheng and Hu, 2023). Transit-oriented development (TOD) has emerged as a strategic planning approach to mitigate urban sprawl and environmental degradation by promoting compact, walkable, and mixed-use neighborhoods centered around public transportation systems (Stojanovski, 2020; Kamruzzaman *et al*., 2018; Ma and Chen, 2019). By leveraging this foundation, green TOD embraces the concepts of green urbanism, which include energy-efficient design, low-emission infrastructure, and the addition of urban green space (UGS), to foster sustainability and bolster urban climate resilience (Cervero and Sullivan, 2011; Calthorpe, 1993). Compared to conventional urban expansion, Green TOD has demonstrated the potential to reduce both carbon emissions and energy consumption by approximately 30 to 36 percent (Nahlik and Chester, 2014). The *Daerah Khusus Ibukota*/Special Capital Region (DKI) of Jakarta is home to more than 10.6 million residents (Central Bureau of Statistics, 2023). It functions as the main center for transportation and mobility in the larger Jabodetabek metropolitan region, encompassing Jakarta, Bogor, Depok, Tangerang, and Bekasi. The city has formally adopted a vision to become a transit-oriented city, as stated in Regional Regulation (2024) concerning the regional spatial plan for 2024–2044. Currently, UGS in Jakarta covers only 5.184% of the city's land area—well below the national target of 30%. A An important case of this trade-off is the conversion of the previous Lebak Bulus Stadium, a recognized green space, into a depot for the Jakarta mass rapid transit (MRT) system (Abdullah and Shalihati, 2020). Lebak Bulus serves as a strategic TOD located on the southern boundary of DKI Jakarta, functioning as a key gateway for urban mobility and development. Located in the heart of the city, Dukuh Atas plays a significant role as a multi-modal transit hub, uniting the MRT, LRT, Commuter Line, and BRT systems to support seamless connectivity. Meanwhile, Manggarai Station stands out as a high-capacity and strategic TOD, accommodating 726 train trips per day and serving approximately 1.2 million passengers (Directorate General of Railways, 2022; Suryanti and Meilianti, 2018). In 2020, UGS coverage in the Manggarai TOD was only 3.83 percent, indicating a lack of ecological infrastructure (Hasibuan and Mulyani, 2022). In 2022, Lebak Bulus and Dukuh Atas had UGS coverage of 9.95 and 16.06 percent, respectively, within a one-kilometer radius. Both areas saw notable reductions in UGS compared to 2013, before TOD development began. This decrease in UGS area raises significant concerns in light of Jakarta's escalating climate issues. The city faces an intensifying Urban Heat Island effect, with rising ambient temperatures exacerbated by dense built environments (Ulfiasari and Yola, 2022). In 2023, GHG emissions reached 29,664 gigagrams of carbon dioxide (CO_2)-equivalent from direct sources and 33,420 gigagrams from indirect electricity use (Environmental Agency of DKI, 2024). The frequency of major flooding events has also increased to more than twenty annually between 2010 and 2020, largely due to climate change and poor stormwater management (Kurniawan *et al.,* 2024). UGS significantly contributes to the mitigation of environmental hazards through its roles in carbon sequestration, microclimate management, and stormwater absorption. Models and methods that quantify the impacts of green infrastructure are increasingly used to demonstrate their value to policymakers (Vandermeulen *et al.,* 2011). However, the absence of market prices for ecosystem services often leads to their undervaluation (Van Oijstaeijen *et al*., 2020), limiting their prioritization in urban planning. This lack of understanding leads to insufficient institutional backing for green infrastructure, which encompasses blue-green solutions such as urban green space (Wihlborg *et al*., 2019). Stronger evidence—especially economic valuation—can help build a policy and investment case for integrating green space into urban systems (Thorne, 2017). Prior studies into UGS in Jakarta have predominantly examined the static spatial distribution or the overall changes in land use throughout the city. For instance, Hasibuan and Mulyani (2022) reported declining UGS within TODs, but without analyzing temporal progression or ecological performance. Economic valuation of UGS in Jakarta using direct use economic value (Setiawan *et al.,* 2023), and contingent valuation method with

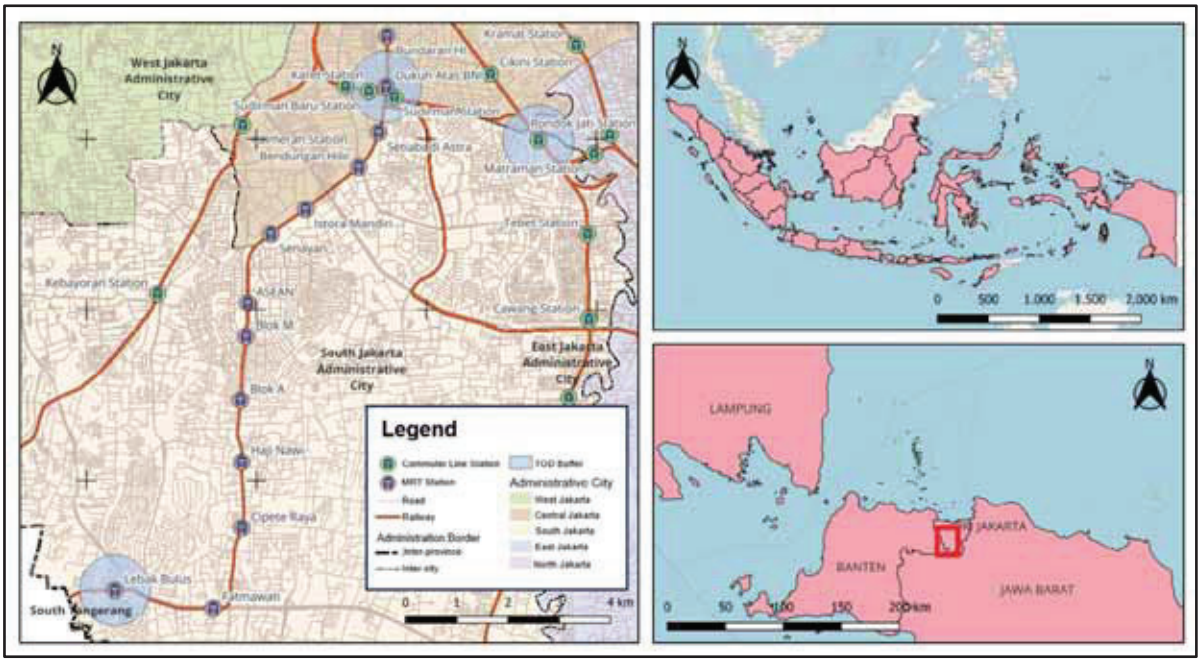

Fig. 1 Geographical location of the study area in Jakarta, Indonesia

willingness to pay (Susetyo *et al.,* 2025; Mahardika and Putri, 2024; Rahmawati *et al.,* 2018) was also conducted with focus on economical aspect, not on its environmental impact. Likewise, Setiowati *et al.* (2024a; 2024b) implemented hedonic pricing and life satisfaction techniques to measure UGS value; however, they failed to incorporate spatial dynamics or or frameworks based on ecosystem services. To date, no research in the Indonesian context has employed a spatially explicit, ecosystem service-based valuation—such as the integrated valuation of ecosystem services and trade-offs (InVEST) model—within TOD zones. Longitudinal assessments of UGS in relation to TOD development are also limited in Jakarta's planning literature. This study aims to fill these gaps by being the first empirical application in Indonesia that evaluate urban green space in Jakarta's TOD zones, utilizing spatiotemporal analysis alongside InVEST-based ecosystem service valuation. It focuses on three key TOD areas, examining changes and ecosystem service values over a 12-year period. It also seeks to estimate their economic value based on ecosystem services that contribute to climate change mitigation. The insights derived from this study are anticipated to shape evidence-based policy and planning strategies aimed at integrating green infrastructure within Jakarta's TOD framework. This study aims to highlight the often-overlooked monetary benefits of urban green space in transit-oriented development planning. The study has been conducted in Jakarta in 2024-2025.

MATERIALS AND METHODS

Study area

This study was conducted in three TOD locations in Jakarta: Lebak Bulus, Dukuh Atas, and Manggarai. The selection of these sites was influenced by their strategic significance within Jakarta's public transportation framework and the differing states of their green spaces. The selected TODs are situated across different administrative regions and represent central, peripheral, and integrated multimodal transit functions. Developed by PT MRT Jakarta, Dukuh Atas is positioned in Central Jakarta and functions as a key intermodal hub that connects multiple transport options. Lebak Bulus, located near Jakarta's southern boundary, is part of the same MRT network but differs in its urban structure and administrative setting. Managed by the Indonesian Railways Company, Manggarai Station is a key commuter hub that is part of Jakarta's extensive transport network. The geographical location of the study areas is illustrated in in Fig. 1.

Data collection

UGS in this study includes all vegetated areas, both public and private, as defined by Law No. 26 of 2007 on Spatial Planning and Minister of Public Works Regulation No. 5/PRT/M/2008. Public UGS includes city parks, green corridors, and cemeteries, while private UGS encompasses yards and gardens within residential or commercial properties. Data concerning land cover was retrieved from Google Earth Engine and analyzed with quatantum geographic information system (QGIS) software. It is essential to acknowledge that raster maps from satellite imagery including Google Earth Engine composed of grid-based pixels and may appear pixelated at high zoom levels with low resolution. It has the potential to lower interpretability and constrain precision when it comes to capturing subtle spatial details. While Google Earth Engine imagery offers strong geometric accuracy for Land Use/Land Cover (LULC) mapping, it performs a little worse for classes requiring high spectral differentiation, such as grassland and woodland (Hu *et al*., 2013). Islami *et al*. (2022) conducted an evaluation of the accuracy of land use change analysis utilizing Google Earth imagery, concluding that the 84% accuracy reached for the 2020 data is considered acceptable and reflects good reliability. However, in this study, to minimize inaccuracy, land cover classification was conducted through manual digitization using Google Earth Pro. The selected datasets aim to depict various stages of TOD development phases: pre-construction (2013), transitional implementation (2019), and anticipated post-development (2025). The spatial analysis was conducted using QGIS software to identify and quantify UGS within each TOD zone. 700-meter buffer was applied around each station to delineate the TOD boundary. This distance is in accordance with international TOD planning standards, which typically define TOD influence zones within a 400 to 800-meter range—translating to a walking distance of 5 to 10 minutes (min.). (Anwar *et al*., 2024). Studies that use 700 meters for the TOD radius including Bertolini (1999); Vale (2015); Wahyulina and Lisa (2020); and Zhang *et al*. (2023). The selection of 700 meters is also consistent with Jakarta Governor Regulation No. 67 of 2019 and the spatial planning guidelines of PT MRT Jakarta, ensuring compatibility with local regulatory frameworks and pedestrian accessibility norms. To facilitate the economic assessment of ecosystem services utilizing the InVEST tool, pertinent secondary data was sourced from diverse origins. The valuation of carbon storage and sequestration was based on Indonesia's estimated social cost of carbon (SCC), ranging between United States Dollar (USD) 32.6 and USD 38.8 per metric ton of CO_2 (Maulana, 2024). The global SCC estimates, as reported by The European Institute on Economics and The Environment, indicate a range from USD 528/ton CO_2 to $975/ton CO_2. Indonesia's SCC is relatively lower than other major fossil-producing countries but higher than neighboring ASEAN countries. For this study, the lower-bound value (USD 32.6 per metric ton of CO_2) was used. The model incorporated an annual growth rate of 23%. A discount rate of 5% were assumed based on a study by Global Green Growth Institute, (2016), reflecting the strong influence of climate change and long-term environmental impacts. Urban cooling services were valued based on potential energy savings using the national electricity tariff of USD 0.089/kilowatt-hour (kWh) for small residential and medium-scale businesses. The calculation of stormwater retention value was based on the costs of replacing the infrastructure needed for retention. A review of relevant literature and construction cost data in Indonesia revealed a range between USD 4.43 and USD 98.7 per cubic meter (m^3) (Fatihah Fhoenna, 2021; Evita, 2022; Florince *et al*., 2015; Hasnani, 2023; Sari *et al*., 2014). For consistency, the median cost value of USD 21.04 per cubic meter was adopted in this study. The assumptions applied to input variables significantly influence the sensitivity and accuracy of the valuation model; achieving a better match between these assumptions and the actual conditions boosts the trustworthiness of economic estimates. Therefore, input variables in this study were specified to the Indonesian context. A comprehensive list of the input variables used for the InVEST modeling and valuation of UGS is presented in Table 2.

Data analysis

A quantitative strategy was utilized to assess the spatiotemporal dynamics of urban green areas and their economic significance in climate-related ecosystem services.

Spatial analysis

A quantitative spatial analysis was conducted to evaluate UGS coverage and change within each TOD.

Table 1: Selection of ecosystem service related to climate change mitigation

No.	Authors	Article title	Ecosystem service related to climate change mitigation	
1.	Amini Parsa *et al.*, 2019	Evaluating the potential contribution of urban Ecosystem service to climate change mitigation	1.	Carbon storage and sequestration
			2.	Urban cooling
2.	Sun *et al.*, 2019	Valuing urban green spaces in mitigating climate change: A city-wide estimate of aboveground carbon stored in urban green spaces of China's Capital	1.	Carbon storage and sequestration
3.	Muluneh and Worku, 2022	Contributions of urban green spaces for climate change mitigation and biodiversity conservation in Dessie city, Northeastern Ethiopia	1.	Carbon storage and sequestration
4.	Fryd *et al.*, 2011	The role of urban green space and trees in relation to climate change	1.	Urban cooling
			2.	Stormwater retention
5.	Demuzere *et al.*, 2014	Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure	1.	Carbon storage and sequestration
			2.	Stormwater retention
			3.	Climate regulation
			4.	Stormwater purification
			5.	Air purification

Using QGIS, the land cover data, time-series analysis was used to assess the dynamics of UGS. Descriptive statistics were used to quantify changes in total UGS area, ownership type (public vs. private), and land condition (maintained vs. idle). In this study, the land cover classification is founded on satellite imagery that has been previously validated through field verification conducted within a wider cluster research project, guaranteeing an acceptable level of accuracy for spatial analysis.

Economic valuation of ecosystem services

To complement the spatial analysis, the study applied the InVEST model to estimate the economic value of UGS-related ecosystem services. InVEST was selected based on the comparative analysis by Van Oijstaeijen *et al*. (2020) on ten valuation toolkits, which identified it as one of three GIS-based urban green infrastructure valuation tools with a robust scientific foundation. Among these, InVEST adopts parameters that are more widely applicable, increasing its flexibility across a range of contexts. The evaluation emphasized three services that are significant for change mitigation: carbon storage and sequestration, urban cooling, and stormwater retention (Amini Parsa *et al*., 2019; Fryd *et al*., 2011; Demuzere *et al*., 2014; Sun *et al*., 2019; Muluneh and Worku, 2022). The decision to select these three ecosystem services was derived from literature that discusses the climate change mitigation functions of UGS, as summarized in Table 1.

These services were modelled using raster-based LULC data with a spatial resolution of 14 × 14 meters, derived from satellite imagery. All model included biophysical and socio-economic variables to create spatially explicit results along with their associated economic estimates. The vector maps used for spatiotemporal dynamics analysis were converted into raster maps for economic valuation. Each raster pixel represents a specific LULC class, which in this study includes UGS, built-up area, and water body. Each LULC class is assigned distinct biophysical parameters for economic valuation analysis. For instance, in the case of carbon storage services, the carbon pool data used to calculate carbon stock varies by LULC class. Likewise, biophysical characteristics including albedo, shade, crop coefficients, and the rise in consumption for urban cooling services are distinct for each LULC class. The runoff coefficient used for valuing stormwater retention services also varies accordingly. By applying respective price or cost calculations to carbon storage, cooling capacity, and retention volume as per the valuation formulas, the economic value of each ecosystem service was derived. This strategy is trustworthy as it fulfills the standards set by the InVEST model. This combined method facilitates an extensive analysis of the ecological function and economic contribution of UGS in the TOD zones of Jakarta. The carbon storage valuation model estimates net carbon stored in land

parcels over time and converts it into economic value using market prices (Natural Capital Project, 2025). In this study, the model applied a carbon price of USD 32.6 per metric ton (Mt), with an assumed annual price increase of 23% and a discount rate of 5% to account for the time value of money. Included in the model outputs are spatial maps that illustrate the total carbon stock and the corresponding financial value of carbon sequestration. These outputs provide a spatially explicit understanding of the carbon-related climate mitigation potential of urban green space within each TOD area. The value of carbon storage over time for a given land parcel x, using Eq. 1 (Natural Capital Project, 2025):

$$value_seq_x = V\frac{s_x}{q-p}\sum_{t=0}^{q-p-1}\frac{1}{\left(1+\frac{r}{100}\right)^t\left(1+\frac{c}{100}\right)^t} \quad (1)$$

Where;

V = price per metric ton of carbon

s_x = amount of carbon, in metric tons, sequestered in a given land parcel

q = future year

p = current year

r = annual market discount rate for carbon price

c = annual carbon price growth rate

Eq. 1 calculates the total present value of carbon sequestered on land parcel *x* over a time period from year *p* to *q*. The formula distributes that carbon benefit evenly across the years *(q - p)*. The summation determines the present value of annual carbon benefits for each year, which is then modified according to the total amount of sequestered carbon and its price. In the economic valuation model for the urban cooling ecosystem service, one applicable method is to calculate energy savings. Energy savings refer to estimated reductions in energy costs driven by the temperature-lowering effects of UGS-based urban cooling. The model inputs include evapotranspiration maps, LULC data, building footprint vectors, biophysical tables, and energy consumption values. It also incorporates meteorological parameters such as a reference air temperature of 25 degrees Celsius (°C), a UHI effect of 6°C, relative humidity of 76%, and spatial thresholds for cooling effects. The differences in evapotranspiration raster maps for each location illustrate the microclimatic variations present in each TOD. Meanwhile, variables such as humidity levels and the UHI effect were similar across the three TODs due to their relatively close spatial proximity. The cooling benefit is valued using the national electricity tariff of USD 0.089/kWh. The outputs generated are a raster map of the Heat Mitigation Index and the estimated value of energy savings, calculated using Eq., 2 (Natural Capital Project, 2025):

$$Energy.\,savings(b) = consumption.increase(b)\cdot\left(\overline{T_{air,MAX}-T_{air,i}}\right)\cdot cost(b) \quad (2)$$

Where;

consumption.increase(b) (kWh/°C/m²) = local estimate of increased energy consumption per degree Celsius per square meter of building footprint, for building category *b*.

$T_{air,MAX}$ (°C) = maximum air temperature across the landscape;

$T_{air,MAX}$ - $T_{air,i}$ (°C) = average air temperature difference for building *b*.

cost(b) = estimated energy cost per kWh for building category *b*, most likely uniform across all buildings.

Eq. 2 estimates the energy savings provided by vegetation in a building category *b* due to reduced cooling demand. The temperature difference term is derived from the Heat Mitigation Index (HMI), a raster map output from InVEST that quantifies how effectively green spaces cool surrounding areas. The HMI reflects the impact of urban green space—such as trees and grass—on lowering surface temperatures. Higher HMI values in green areas lead to improved cooling effects, which create larger temperature differences and thus increase potential energy savings. In the economic valuation model for stormwater retention, a calculation is performed to determine the value of retained water (V_{RE}). The inputs in this model include: a raster map of LULC, a raster map of hydrologic soil groups, a raster map of rainfall, a biophysical table, and a replacement cost (PR) of USD 21.04. These inputs yield outputs represented as raster maps for both retention volume and the economic value of stormwater retention, determined using Eq., 3 (Natural Capital Project, 2025):

$$Retention.\,cost = PR\cdot V_{RE} \quad (3)$$

Eq. 3 estimates how much monetary value is saved by retaining stormwater through natural green infrastructure rather than using built infrastructure.

Table 2: Workflow of inVEST model

Model	Input	Description	Process	Output
Carbon storage and sequestration	Baseline LULC (raster)	A map of LULC for the baseline scenario, which must occur prior to the alternate scenario.	Calculate sequestration	Total carbon storage, Raster map of carbon storage
	Carbon pools (csv)	A table that maps each LULC code to carbon pool data for that LULC type.		
	Alternate LULC (raster)	A map of LULC for the alternate scenario, which must occur after the baseline scenario.		
	Price of carbon (currency units/t)	The present value of carbon.	Run valuation model	Total economic value, Raster map of economic value from carbon storage
	Annual market discount rate (%)	The price of carbon, which reflects society's preference for immediate benefits over future benefits.		
	Annual price change (%)	The relative annual change of the price of carbon.		
Urban cooling	LULC (raster)	Map of LULC for the area of interest.	Calculate heat mitigation index	Raster map of heat mitigation index
	Reference evapotranspiration (raster)	Map of reference evapotranspiration values.		
	Area of interest (vector)	A map of areas over which to aggregate and summarize the final results.		
	Biophysical table (csv)	A table mapping each LULC code to biophysical data for that LULC class.		
	Reference air temperature (°C)	Air temperature in a rural reference area where the urban heat island effect is not observed.		
	UHI effect (°C)	The magnitude of the urban heat island effect, i.e., the difference between the rural reference temperature and the maximum temperature observed in the city.		
	Air blending distance (m)	Radius over which to average air temperatures to account for air mixing.		
	Maximum cooling distance (m)	Distance over which green areas larger than 2 hectares have a cooling effect.		
	Building (vector)	A map of built infrastructure footprints.	Run energy savings valuation	Energy savings economic value, Vector map of energy savings economic value
	Energy consumption table (csv)	A table of energy consumption data for each building type.		
Stormwater retention	LULC (raster)	Map of LULC for the area of interest.	Run stormwater retention valuation	Stormwater retention volume, Raster map of stormwater retention volume, Stormwater retention value, Vector map of stormwater retention value
	Soil hydrologic group (raster)	Map of soil hydrologic groups. Pixels may have values 1, 2, 3, or 4, corresponding to soil hydrologic groups A, B, C, or D, respectively.		
	Precipitation (raster)	Map of average annual precipitation.		
	Biophysical table (csv)	Table mapping each LULC code found in the LULC raster to biophysical data about that LULC class.		
	Area of interest (vector)	Areas over which to aggregate results (typically watersheds or sewersheds).		
	Replacement cost (currency/m^3)	Replacement cost of stormwater retention devices		

The unit volume replacement cost, indicating the financial outlay for creating artificial infrastructure, including retention ponds or stormwater drains, to address runoff. The retention volume is determined by modeling how much rainwater is captured or absorbed by UGS instead of flowing over impervious surfaces. The runoff coefficient plays a crucial role in determining this volume, as it represents the permeability of various land cover types. The greater the volume of water retained by UGS, the higher the cost savings, reinforcing the economic importance of preserving or expanding green areas in cities. The workflow of InVEST model is explained in Table 2.

The projected economic value is subsequently

modified with a discount rate to reflect the diminishing economic value as time progresses. A calculation of present value (PV) is required, in which the year 2025 is considered as the Future Value (FV) relative to the base year 2013. In order to calculate this discounting, it must be used Eq. 4 (Brealey *et al*., 2020):

$$PV = FV\frac{1}{(1+r)^n} \quad (4)$$

With the following notation:
PV = Present Value
FV = Future Value
r = discount rate (in decimal)
n = number of periods

There are limitations and uncertainties inherent in the modeling and output estimation processes, particularly regarding the variability in carbon price forecasts, and socio-economic factors that may influence the valuation metrics. This study excludes indirect economic benefits (for instance, health and productivity) due to limitations in valuation and methodological restrictions in quantifying wider economic advantages. Additional uncertainties arise from potential classification errors in the satellite-derived land cover data and the use of generalized biophysical coefficients within the InVEST models. Additional ambiguity is derived from the established parameters concerning carbon pricing, electricity tariffs, and the expenses linked to infrastructure replacement. Future studies ought to include uncertainty analysis methods—such as scenario comparisons or sensitivity analysis—to enhance the robustness of ecosystem service valuations and facilitate evidence-based decision-making.

RESULTS AND DISCUSSION

Spatiotemporal dynamics of UGS land cover in TOD areas

Lebak Bulus TOD

In 2013, prior to the establishment of the MRT system, the total expanse of UGS within the Lebak Bulus TOD buffer zone measured about 73.66 hectares, representing 47.83% of the entire land area. Public UGS included the park adjacent to the Ministry of Public Works complex lake and the former Lebak Bulus Stadium. Private UGS was found in the landscaped grounds of the National Research and Innovation Agency (BRIN), the water utility company PAM Jaya, and idle vegetated land owned by PT Metropolitan Kentjana along T.B. Simatupang Street. With the launch of Jakarta MRT Phase 1 in 2019, the UGS area diminished to 66.01 hectares (42.87%). This reduction was primarily attributed to the conversion of the Lebak Bulus Stadium—previously classified as UGS—into the MRT depot. Furthermore, vegetation was lost on the private property belonging to PT Metropolitan Kentjana. While the remaining green space in BRIN and PAM Jaya complexes was maintained, there was no significant expansion of public UGS. By 2025, the UGS coverage in the Lebak Bulus TOD increased substantially to 105.33 hectares (68.39%). This improvement was connected to the reestablishment of green belts, the development of vegetation on land that was previously idle and owned by PT Metropolitan Kentjana and the Jakarta Provincial Government (located east of the MRT depot), along with a rise in planting within institutional grounds like BRIN. Nevertheless, the majority of UGS remained under private ownership, with public UGS limited to the area around the Ministry of Public Works. Certain designated UGS plots, such as the RW 02 Cemetery Park, lacked dense vegetation. The spatial distribution of UGS in the Lebak Bulus TOD is presented in Fig. 2.

Dukuh Atas TOD

In 2013, the Dukuh Atas TOD area contained 77.64 hectares of UGS, representing 50.42% of the total land area. Public green spaces included Sumenep Park, Lawang Park, Panarukan Park, and riparian buffers along the Ciliwung River adjacent to the Sudirman Commuter Line Station. A large segment of UGS was made up of unoccupied private land, including the vacant area southeast of Wisma Indocement, land east of Kebon Melati Reservoir, and parcels found west of Baturaja Street. By 2019, following the completion of Dukuh Atas MRT Station and BNI City Station, UGS in the TOD zone increased modestly to 83.12 hectares (53.98%). The increase can be attributed in part to the vegetative modification of a wetland area to the south of Jalan Galunggung. However, some riparian UGS—particularly near the Ciliwung River—was converted into built-up areas for BNI City Station. Other losses occurred due to the construction of Thamrin Nine (Agora Mall) and early-stage development of the Fifty Seven Promenade Apartments. In 2025, UGS within the Dukuh Atas TOD increased further to 89.08 hectares (57.84%).

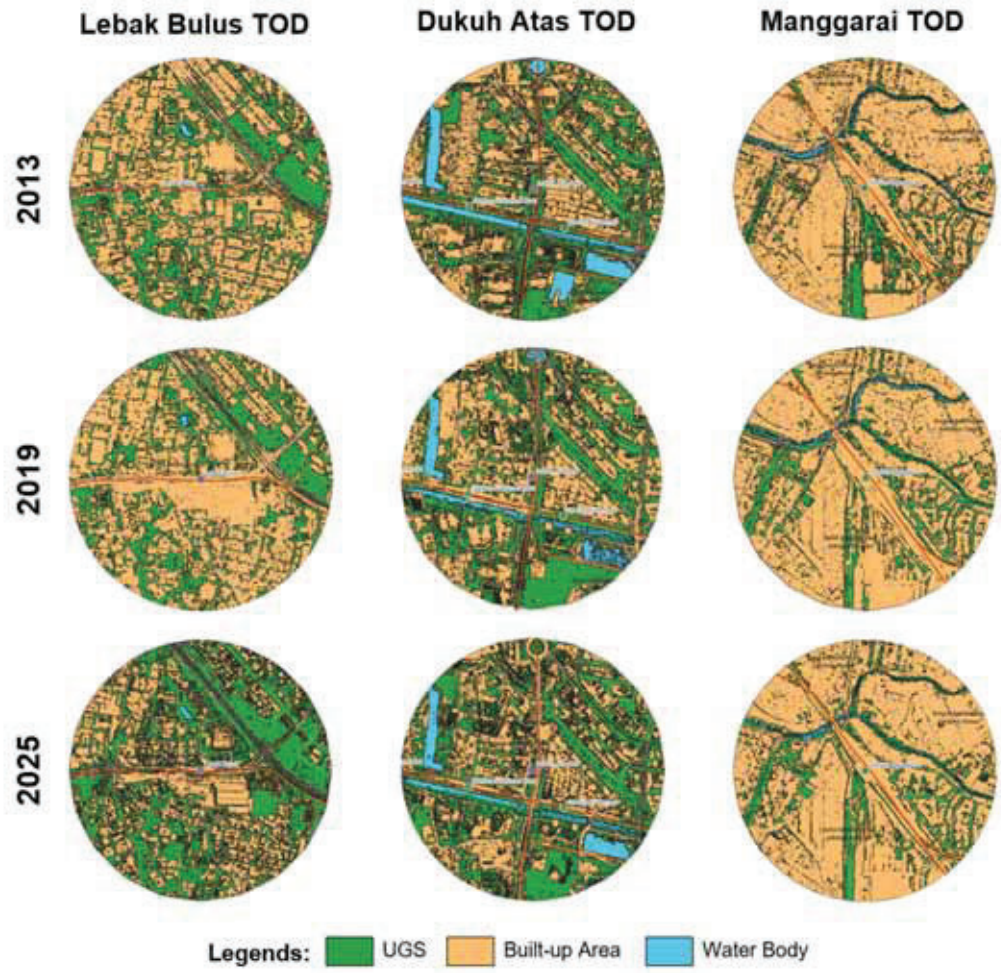

Fig. 2: Map of UGS land cover in Lebak Bulus TOD, Dukuh Atas TOD, and Manggarai TOD

Green corridors were restored along the Ciliwung River, particularly around BNI City Station. The redevelopment of Sumenep Park led to its renaming as the Sumenep Promenade, while Lawang Park and Panarukan Park were kept intact. Much of the additional UGS was composed of regrown vegetation on idle lands—especially around Wisma Indocement, along K.H. Mas Mansyur Street, and at the edge of Kebon Melati Reservoir where some development had stalled. The updated spatial distribution of UGS is shown in Fig. 2.

Manggarai TOD

The baseline UGS condition in Manggarai TOD in 2013—prior to redevelopment—was documented at 33.54 hectares (21.78%). A significant portion of this green space was situated within railway operational zones administered by PT Kereta Api Indonesia (KAI), encompassing the Manggarai Train Depot. Additional public UGS consisted of riparian zones along the Ciliwung River between Minangkabau Barat and Minangkabau Timur Streets. By 2019, the second year of the Manggarai Central Station revitalization, the UGS area slightly increased to 35.66 hectares (23.16%). Despite a reduction of UGS due to construction, new vegetation was observed on idle plots near the Pasaraya Manggarai parking lot and on vacant land of formerly residential parcels. As of 2025, UGS in Manggarai TOD had grown to 37.38 hectares (24.27%). The rise was ascribed to increased

Table 3: Comparison of changes in UGS area per TOD

TOD	UGS area 2013 (ha)	UGS area 2019 (ha)	UGS area 2025 (ha)	Net Change 2025–2013 (ha)
Lebak Bulus	73.66	66.01	105.36	31.662
Dukuh Atas	77.64	83.12	89.08	11.433
Manggarai	33.54	35.66	37.38	3.839

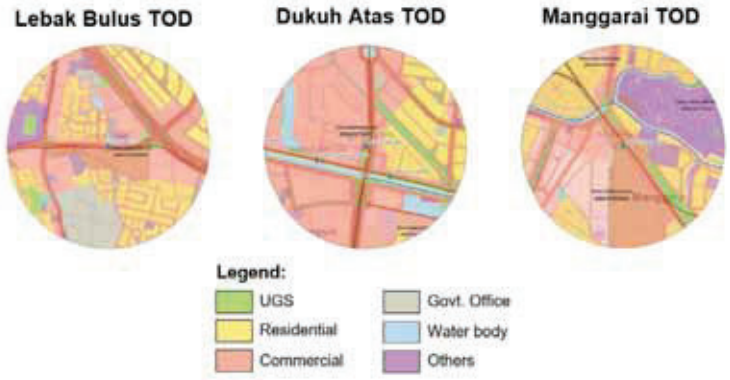

Fig. 3: UGS zoning in Jakarta's Detailed Spatial Plan

vegetative activity on dormant lands located west of the station and in the old Pasaraya Manggarai zone, in addition to landscape upgrades near the PT KAI Train Depot. Fig. 2 presents the 2025 spatial configuration of UGS in the Manggarai TOD zone. Table 3 illustrates the alterations in UGS area among the three designated TOD locations, based on a time-series analysis spanning six years period. The data show that Lebak Bulus TOD consistently had the largest UGS area, followed by Dukuh Atas and Manggarai. All three TODs experienced a net increase in UGS area over the 12-year period. This observation is at odds with prior studies that have shown a suggesting a widespread in UGS coverage throughout Jakarta. In the case of these TOD zones, however, the presence of numerous idle or abandoned plots contributed significantly to vegetative land cover, resulting in an increase in total UGS area. These unassigned lands, while not classified as official UGS in zoning laws, still serve significant ecological purposes. Despite the substantial increase in vegetated land cover, this growth does not align with designated green space zoning in the Jakarta Detailed Spatial Plan. In each of the three TOD areas, land zoned for UGS accounts for less than 10% of the total UGS observed, as zoning regulations typically include only publicly owned or accessible green space (Fig. 3). This inconsistency underscores an important concern: despite the substantial spatial presence of UGS, the quality, accessibility, and legal protections for these areas are still restricted. A large share of UGS consists of idle, privately owned land that can be reclassified or developed at any time, potentially leading to the loss of its ecological functions. In this context, economic valuation serves as a strategic tool to quantify the ecological and monetary benefits of UGS. It can help policymakers recognize the hidden value of green infrastructure and prioritize mechanisms such as incentives, zoning revisions, or conservation regulations to preserve and expand UGS in TOD areas.

Economic valuation of UGS ecosystem services in TOD Areas

The results demonstrate that all three TOD areas experienced growth in the economic value of ecosystem services over time, with Lebak Bulus TOD contributing the highest total value by 2025. The study underscores the vital contribution of stormwater retention to the overall comprehensive, in addition to urban cooling and carbon sequestration. These findings underscore the need to prioritize UGS integration in TOD planning as a nature-based solution for urban climate resilience.

Lebak Bulus TOD

2013

Given that the InVEST model needs both a baseline year and an alternate year for carbon valuation, carbon storage was not assigned any economic value in 2013. However, the model estimated a total carbon stock of 19,200 metric tons of CO_2 (Fig. 4). The Heat Mitigation Index for urban cooling ranged from 0.265 to 0.84 (Fig. 5), corresponding to an energy savings value of USD 2.59 million. For stormwater retention, the UGS retained 625,246 meter cubic (m^3) of runoff, valued at USD 13.16 million (Fig. 6). Consequently, the overall economic worth of UGS in Lebak Bulus TOD for the year 2013—without considering carbon sequestration—amounted to USD 15.75 million.

2019

Carbon stock decreased to 16,779 metric tons, resulting in a negative valuation of –USD 45.86 thousand, indicating a loss in carbon storage relative to 2013. The Heat Mitigation Index was consistent, ranging from 0.23 to 0.84, which led to energy savings amounting to USD 2.46 million. Stormwater retention declined to 380,453 m^3, valued at USD 8 million. The total estimated economic value in 2019 was USD 10.42 million.

2025

The carbon stock is projected to grow significantly by 2025, achieving 27,287 metric tons and producing a beneficial economic value of USD 93.1 thousand. The Heat Mitigation Index slightly improved (0.37–0.84), with an energy savings value of USD 2.51 million. Stormwater retention increased to 843,718 m^3, with an economic value of USD 17.75 million. The total estimated value of ecosystem services in 2025 was USD 20.36 million.

Dukuh Atas TOD

2013

Given the lack of a baseline for carbon valuation, the evaluation focused solely on the carbon stock, which reached a total of 21,133 metric tons of CO_2 (Fig. 4). The Heat Mitigation Index ranged from 0.29 to 0.84 (Fig. 5), corresponding to an energy savings value of USD 2.34 million. UGS retained 489,580 m^3 of runoff, valued at USD 10.3 million (Fig. 6). The total value of ecosystem services was USD 12.65 million.

2019

Carbon stock increased to 22,234 metric tons, yielding an economic value of USD 20.85 thousand. The Heat Mitigation Index remained stable, with energy savings valued at USD 2.39 million. Stormwater retention totaled 407,166 m^3, with a value of USD 8.57 million. The overall value of ecosystem services in 2019 amounted to USD 10.98 million.

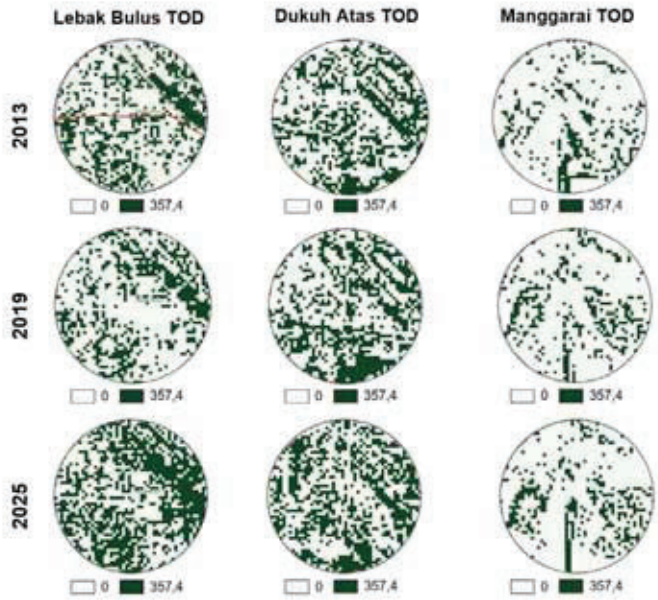

Fig. 4: Carbon Storage of UGS

2025

Carbon stock further increased to 23,968 metric tons, with an associated economic value of USD 32.63 thousand. The Heat Mitigation Index enhanced to a range of 0.36 and 0.84, achieving energy savings of USD 2.49 million. UGS retained 550,385 m³ of runoff, valued at USD 11.58 million. The total estimated value of UGS ecosystem services in Dukuh Atas TOD

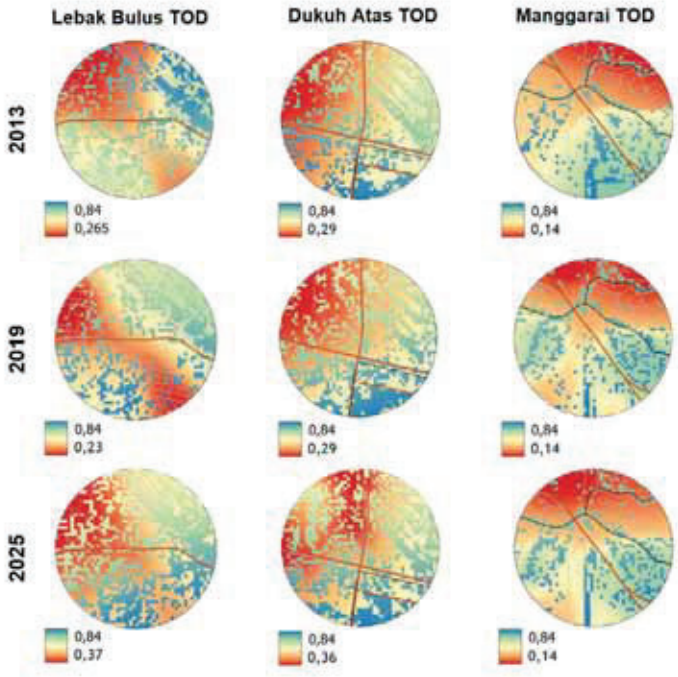

Fig. 5: Heat Mitigation Index per pixel in TODs

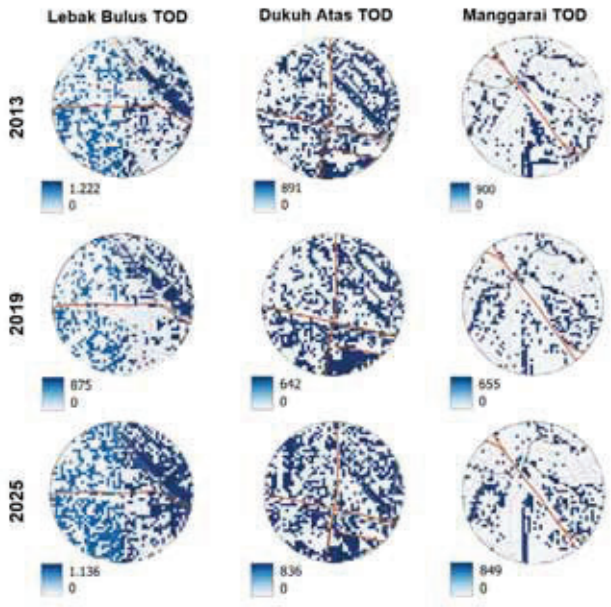

Fig. 6 Retention Volume of UGS in TODs

in 2025 was USD 14.1 million.

Manggarai TOD

2013

The initial carbon stock in UGS was 8,971 metric tons of CO_2. No economic value was assigned due to the absence of comparative data. The Heat Mitigation Index ranged from 0.14 to 0.84, resulting in an energy savings value of USD 1.79 million. Stormwater retention was estimated at 198,451 m^3, valued at USD 4.18 million. The total estimated value of ecosystem services was USD 5.97 million.

2019

Carbon stock increased to 9,769 metric tons, with a corresponding economic value of USD 15.12 thousand. The Heat Mitigation Index was consistent, with energy savings calculated at USD 1.91 million. Stormwater retention decreased to 156,160 m^3, valued at USD 3.29 million. The total value in 2019 was USD 5.21 million.

2025

By 2025, carbon stock reached 10,181 metric tons, generating an economic value of USD 13.94 thousand. The energy savings from urban cooling remained at USD 1.96 million, accompanied by a stable Heat Mitigation Index range. UGS managed to retain 227,432 m^3 of stormwater, which equates to a value of USD 4.79 million. The total value of ecosystem services in Manggarai TOD in 2025 was USD 6.76 million.

The economic valuation results reveal substantial variation in the ecosystem service benefits provided by UGS across the three TOD areas. The estimated values ranged from USD 3.76 million in Manggarai TOD in 2025 to USD 15.75 million in Lebak Bulus TOD in 2013. In every reference year, Lebak Bulus maintained the highest economic value, trailed by Dukuh Atas and Manggarai. This consistent hierarchy illustrates a significant positive correlation between the spatial extent of UGS and the financial value of ecosystem services delivered. Among the three services assessed, stormwater retention emerged as the largest contributor to the total economic value, particularly in TODs with larger vegetated catchments. This underscores the vital hydrological function of UGS in urban settings with high density by alleviating runoff, decreasing flood risk, and minimizing the costs associated with public infrastructure. The urban cooling service, captured through energy savings, also contributed significantly, indicating the importance of vegetation in regulating microclimate conditions within transit-oriented districts. Carbon sequestration, while valuable, accounted for a smaller share of the total value, partly due to the relatively limited biomass and canopy cover typical of inner-city UGS. In spite of favorable economic indicators, the analysis uncovers a serious weakness: a considerable share of the UGS—particularly in Lebak Bulus and Dukuh Atas—is situated on dormant or privately owned property. These green spaces, though vegetated and ecologically functional, lack formal protection under existing zoning regulations and may be subject to conversion. As a result, their future contribution to climate mitigation remains uncertain. This underscores the importance of TOD planning strategies aimed at not just expanding green space coverage but also guaranteeing its legal status, accessibility, and ecological functionality. The observed patterns reinforce the role of UGS as essential infrastructure in addressing urban climate challenges. In the context of TOD, where high density and impervious surfaces are predominant, the multifunctional role of green space becomes even more significant. Consequently, the incorporation of UGS in TODs should be viewed not just as an extra design component, but as a strategic investment in urban resilience. It delivers both public and private benefits through reduced environmental risks, improved thermal comfort, enhanced stormwater management, and overall livability. Similar study performed in global settings bolster the legitimacy of the economic valuation findings discussed in this study. For instance, in a study conducted in Cape Town, South Africa, de Wit *et al*. (2009) estimated the economic value of ecosystem services provided by UGS at ZAR 60,412,381, which is approximately USD 3.37 million. This valuation aligns with the range of economic values identified for Jakarta's TODs. Similarly, Kadaverugu *et al*. (2020) assessed the flood prevention benefits of UGS in Hyderabad, India, using the InVEST model, and reported an economic value of USD 1.39 million. In Shenzhen, China, Hamel *et al*. (2021) calculated the ecosystem service value of UGS at USD 8.5 million. These international case studies demonstrate that the economic valuation outcomes of UGS in Jakarta's TOD zones—varying from USD

Table 4: Economic Value of UGS ecosystem service per TOD per year (in USD)

TOD	Year	Economic value of UGS Ecosystem service			Total
		Carbon storage and sequestration	Urban cooling	Stormwater retention	
Lebak Bulus	2013	–[1]	2,593,697	13,157,108	15,750,805
	2019	-45,855	2,456,037	8,005,901	10,416,084
	2025	93,103	2,514,756	17,754,423	20,362,282
Dukuh Atas	2013	–[1]	2,342,736	10,302,267	12,645,003
	2019	20,851	2,390,499	8,568,035	10,979,385
	2025	32,630	2,485,282	11,581,804	14,099,717
Manggarai	2013	–[1]	1,792,269	4,176,018	5,968,286
	2019	15,117	1,910,697	3,286,092	5,211,905
	2025	13,939	1,957,116	4,785,866	6,756,921

[1] *Economic value of carbon sequestration was not calculated for 2013 due to the absence of baseline comparison data required by the InVEST model.*

Table 5: Economic value of UGS ecosystem services per TOD per Year Adjusted to 5% discount rate (in USD)

TOD	Year	Economic value of UGS Ecosystem service			Total
		Carbon storage and sequestration	Urban cooling	Stormwater retention	
Lebak	2013	–[1]	2,593,697	13,157,108	15,750,805
Bulus	2019	-34,217	1,832,732	5,974,127	7,772,642
	2025	51,843	1,400,310	9,886,327	11,338,481
Dukuh Atas	2013	–[1]	2,342,736	10,302,267	12,645,003
	2019	15,559	1,783,827	6,393,600	8,192,986
	2025	18,170	1,383,898	6,449,182	7,851,250
Manggarai	2013	–[1]	1,792,269	4,176,018	5,968,286
	2019	11,280	1,425,791	2,452,132	3,889,204
	2025	7,762	1,089,796	2,664,949	3,762,506

[1] Economic value of carbon sequestration was not calculated for 2013 due to the lack of baseline data required by the InVEST model.

3.76 million to USD 15.75 million—are in agreement with global benchmarks. This supports the robustness and plausibility of the InVEST-based estimates used in this study. Nonetheless, it is essential to note that, up to this point, there is an absence of local studies in Indonesia that implements the InVEST model for urban green spaces. Most Indonesian applications of the InVEST tool have focused on non-urban ecosystems, such as watersheds and lakes (Nahib *et al.*, 2024; Supriyanto *et al.*, 2024), mangrove forests (Marlianingrum *et al.*, 2021), coastal areas (Tussadiah *et al.*, 2021), peatlands (Song *et al.*, 2024), and others. The unavailability of relevant literature impedes the ability to directly corroborate the outcomes of this study against comparable research performed in the national context. Future research on the economic valuation of urban UGS in Indonesian cities using ecosystem service models such as InVEST is therefore recommended. Table 4 presents a summary of the anticipated economic value of UGS ecosystem services by TOD and year. These figures represent the gross values derived from the InVEST model prior to adjustment for temporal value depreciation. To account for the time value of money, a 5% annual discount rate was applied to generate adjusted present values, as shown in Table 5. These lowered figures establish the groundwork for comparison with worldwide benchmarks. The negative carbon value observed in 2019 reflects a net reduction in carbon stock compared to the 2013 baseline. The InVEST model estimates economic value based on the change in carbon storage between two time points. Therefore, a decrease in vegetated land cover or tree biomass in 2019 results in a negative valuation. This does not represent an expense, but rather a decline in the value of ecosystem services caused by a lowered capacity for carbon sequestration.

Figs. 8, 9, and 10 disaggregate the economic

value of each individual ecosystem service by TOD and year, offering a clearer view of their respective patterns. As shown in Fig. 8, the carbon storage value for 2013 is assumed to be zero, as the InVEST model requires both a baseline and an alternative year to compute net changes. In 2019, the Lebak Bulus TOD experienced a decrease in carbon storage, with carbon stock falling from 19,200 to 16,779 metric tons as a result of UGS conversion for MRT development. By 2025, a significant rebound occurs, driven by the expansion of vegetated land, which increases carbon stock to 27,287 metric tons, thereby yielding a positive valuation. In Dukuh Atas and Manggarai, the rise in UGS coverage from year to year is quite minimal, leading to only slight enhancements in carbon storage value. Notably, in Manggarai, the 2025 value is lower than in 2019 due to the application of the discount rate, which reduces the present value of future ecosystem service benefits.

Fig. 9 illustrates that the economic value of urban temperature regulation via UGS declines across all TODs over time, even in cases where UGS coverage increases. This paradoxical trend is linked to the cumulative nature of the 5% annual discount rate, which lowers future financial gains, combined with the inconsistencies in reference evapotranspiration inputs applied annually. For instance, evapotranspiration was highest in 2013, contributing to a higher valuation despite smaller UGS areas. In Lebak Bulus, UGS decline led to a significant drop in cooling value, and the 2025 recovery remained insufficient to offset prior losses and discounting effects. Manggarai TOD, which has the least UGS area, records the lowest economic value, whereas

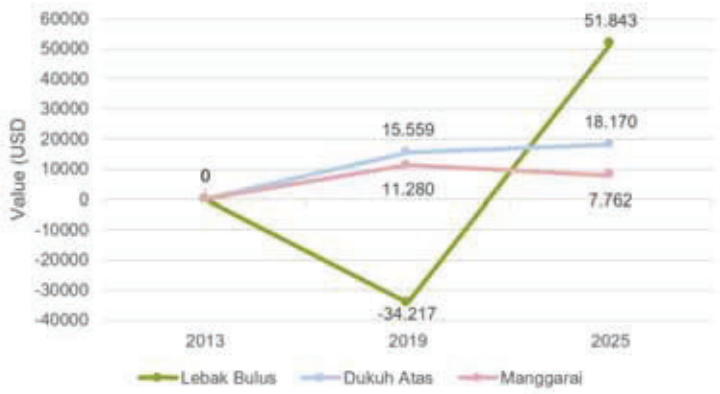

Fig. 8: Economic value of carbon storage ecosystem service

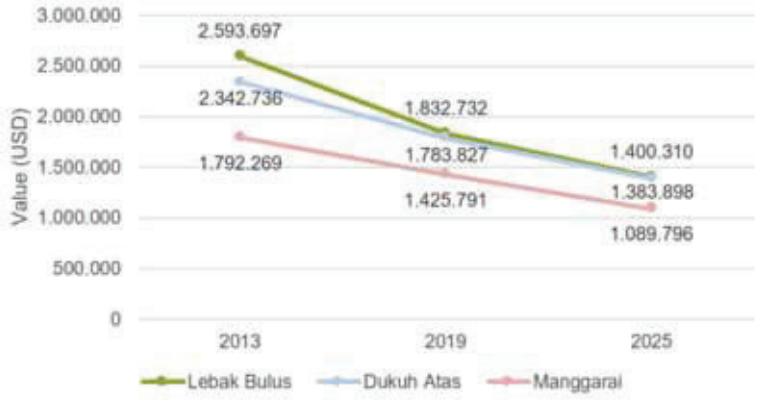

Fig. 9: Economic value of urban cooling ecosystem service

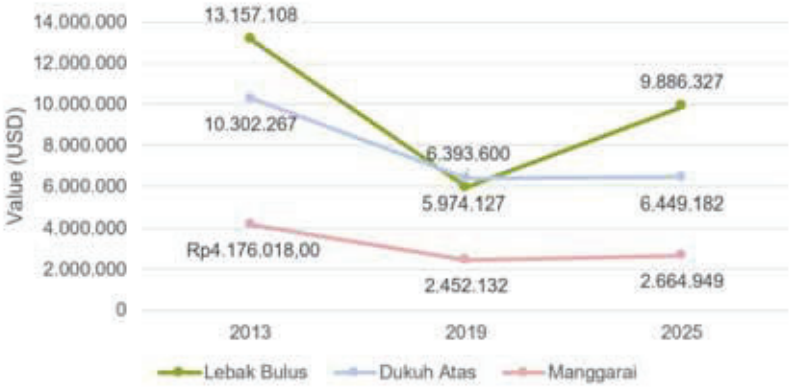

Fig. 10: Economic value of stormwater retention ecosystem service

Dukuh Atas and Lebak Bulus follow a value gradient that mirrors their respective green space extents. These outcomes correspond with ecological theory indicating that increased vegetation density boosts shading and evapotranspiration, thus improving cooling efficiency and decreasing energy expenses.

As shown in Fig. 10, the stormwater regulation value is again highest in Lebak Bulus TOD, followed by Dukuh Atas, and lowest in Manggarai—a pattern consistent with the total UGS area available for runoff absorption. In 2019, a sharp decline in value is observed across all TODs. The decrease is linked not just to UGS loss in regions such as Lebak Bulus, but also to the diminished annual precipitation figures employed as raster inputs for that year. In contrast, the high stormwater retention value in 2013 is linked to greater rainfall—corresponding with one of Jakarta's most severe flood years. By 2025, a moderate recovery in value occurs, in line with expanded UGS coverage; however, the present value remains below 2013 levels due to the discount factor. These outcomes emphasize the significance of vegetated areas as a budget-friendly nature-based strategy for reducing the risk of urban flooding.

Spatiotemporal analysis reveals that UGS land cover in the three TOD areas increased. This is in conflict with the preliminary hypothesis suggesting that TOD development causes a reduction in UGS as a result of land being repurposed for residential, commercial, and transport infrastructure. This study's findings differ from Hasibuan and Mulyani (2022), who reported lower UGS coverage in all three TODs within a 1 km buffer in 2020, indicating a possible shift due to policy or land cover changes. The discrepancy may stem from differences in data approaches. In this study, satellite imagery from Google Earth Engine is used for analyzing land cover, while alternative studies may utilize land use maps. Land cover is defined as the biophysical materials found on the surface, including vegetation, water, and impervious surfaces. Conversely, land use describes the ways in which humans make use of land and its resources (Campbell and Wynne, 2011). International evidence also reflects variation in TOD impacts on green space. For instance, Mukhamedjanov *et al*. (2021) found a reduction in green areas in Tokyo due to TOD implementation, while in Delhi, India, Patill and Singh (2024) reported that TOD planning has prioritized UGS creation, emphasizing its benefits for community well-being. In Jakarta, the growth of UGS may be somewhat ascribed to innovative local policies that weave ecological aspects into the planning of urban transport. Jakarta's regional regulations mandate minimum UGS proportions in TOD areas and promote greening initiatives, particularly along pedestrian corridors and road medians. While most national studies report UGS decline—such as the 10% loss identified in Jakarta from 2000 to 2020 by Nurfadhil and Zain (2024). This study highlights a distinct trend in TOD zones. The discrepancy may be due to variations in classification: this study recognizes vegetated idle private land as UGS, in contrast to formal planning documents that exclude it. UGS expansion in TODs is visible in Lebak Bulus (T.B. Simatupang and east of the MRT depot), Dukuh Atas (K.H. Mas Mansyur and Waduk Kebon

Melati), and Manggarai (Pasaraya Manggarai and Dr. Saharjo Street). These areas reflect increased vegetation on idle lands within the TOD zones. The existence of dormant private UGS within TOD brings to light concerns that align with earlier studies. These green spaces are susceptible, and the reduction of private green areas is infrequently balanced by the creation of new public UGS (Haaland and van Den Bosch, 2015). Public UGS in Jakarta's Detailed Spatial Plan is very limited. This points to underutilized urban space that could be better planned. Similar challenges have been observed in other Asian cities. Sung and Oh (2011) found that uneven green space distribution in TOD zones in Seoul reduced accessibility and environmental impact. The risks with private land ownership, including the lack of regulatory mechanisms to secure these areas for permanent green space use. Even though vacant land might momentarily boost urban green spaces, its classification is unclear and at risk of being repurposed. This uncertainty makes it susceptible to alterations. To support long-term green space retention, it is essential to establish formal land-use designations and implement incentives for private land conservation (e.g., tax relief or development rights transfers). These efforts should also be integrated into spatial planning instruments such as green zoning or public-private partnership schemes. Regulatory deficiencies are notably present, especially due to the absence of zoning regulations. Many privately owned green lands are classified as 'idle' or non-developed, without formal zoning designation as public green space. The lack of official acknowledgment renders them susceptible to legal transformation for commercial or residential purposes. The evidence underscores the need for more integrated UGS planning within TOD frameworks—one that balances ecological performance, accessibility, and social function. Comparative examples from Ghana and the Philippines further support these findings. Yawson *et al*. (2019) noted the underutilization of idle land in Ghanaian cities due to poor land use planning, while Faizan (2021) identified similar patterns in Manila's high-value urban zones. Hsiao (2021) observed that in Taipei, rooftop and vacant-lot gardens are less common in areas with superior public transport access, implying a trade-off that can be resolved with more inclusive transit planning. In contrast, Jakarta's TODs already contain significant vegetated idle land within high-access zones, presenting a unique opportunity. Approaches must be devised to turn these dormant lands into publicly available and thriving green spaces. As noted by Yawson *et al*. (2019) and Selamat *et al*. (2023), addressing the tension between urban economic growth and green space preservation requires tools that articulate the tangible benefits of UGS. To help policymakers recognize the hidden value of green infrastructure which is often undervalued, ecosystem service valuation models could be utilized (Vandermeulen *et al*., 2011). Across the three TODs, annual UGS economic values were estimated to range from USD 3.76 million (Manggarai, 2025) to USD 15.75 million (Lebak Bulus, 2013). When a 5% discount rate is utilized, values decline as time progresses, highlighting the temporal sensitivity inherent in economic valuation. Still, within each year, the TOD with the highest UGS coverage consistently yielded the greatest economic value, highlighting a direct positive correlation between spatial extent and monetary benefit. These values are in line with international benchmarks. In Cape Town, South Africa, de Wit *et al*. (2009) valued UGS ecosystem services at ZAR 60.4 million (USD 3.37 million). Kadaverugu *et al*. (2020) estimated the value in Hyderabad, India, at USD 1.39 million, and Hamel *et al*. (2021) reported a valuation of USD 8.5 million in Shenzhen, China. These parallels support the methodology implemented in Jakarta and align its UGS valuations within a range that can be compared globally. Among the three services evaluated, stormwater retention contributed the highest share to total economic value, followed by urban cooling and carbon storage. The diminished value associated with carbon sequestration can be attributed to cautious market pricing and the restricted biomass that is generally present in urban vegetation. In contrast, the economic valuation of temperature regulation and stormwater management relied on replacement cost methods, yielding higher figures based on energy and infrastructure savings. Variations in service values among TODs are mainly due to differences in UGS area. Lebak Bulus, which contains the largest green space, recorded the highest total economic value, followed by Dukuh Atas and Manggarai. Increases in vegetation density, evapotranspiration, and rainfall retention capacity further enhanced service outputs. For instance, more

expansive vegetated regions enhance carbon storage capacity and increase the surface area available for rainwater absorption, thus lowering the risk of flooding and the costs tied to infrastructure. Based on these findings, there is a strong policy imperative to prioritize UGS as a central component of TOD development. Given that a significant portion of existing UGS is situated on unused private land, it is essential to implement strategies that guarantee sustained accessibility and operational effectiveness. Gubernatorial Regulation No. 50 of 2021 enables Gross Floor Area (GFA) incentives, granting developers extra building rights in return for providing public infrastructure, including UGS. International practices offer further inspiration. For example, Qian *et al.* (2019) found that GFA bonuses have successfully incentivized green space provision in East Asian cities. Other resources consist of zoning incentives, financial support for planting trees and installing green roofs, as well as stormwater credit trading (Grant, 2018). The concept of privately owned public spaces, when implemented through stakeholder collaboration and inclusive design, also offers a viable pathway to enhancing UGS access in dense urban environments (To, 2018).

CONCLUSION

This study assessed long-term changes and the economic value of UGS in three TOD areas in Jakarta. What makes this study innovative is its fusion of spatial analysis and the valuation of ecosystem services. To date, few studies in Indonesia have applied InVEST for urban green infrastructure, and even fewer have linked ecosystem service valuation explicitly to TOD planning. This study provides both innovative methodologies and relevant policy insights, illustrating how UGS can function as a strategic ecological and economic resource in the quest for climate-resilient urban transformation. Although green space now covers more than 21% of each area, over 70% of it lies on idle private land that lacks protection under Jakarta's zoning regulations. UGS zoning is less than 10% per TOD, creating a gap between actual green space and what is legally recognized. In the absence of well-defined policies or incentives, these green spaces are vulnerable to conversion, potentially diminishing their long-term environmental and social advantages. Through the application of the InVEST model, the total economic value of UGS in each TOD ranged from USD 3.76 million to USD 15.75 million per year, with stormwater retention consistently contributing the highest value. However, these figures are subject to various assumptions, including the social cost of carbon, evapotranspiration rates, rainfall variability, and a 5% discount rate to reflect present value. Consequently, the outcomes should be understood as representative rather than conclusive. Jakarta's zoning regulations should be revised to formally recognize vegetated idle land as part of the city's green infrastructure network. Integrating UGS spatial data and ecosystem service valuation into the Detailed Spatial Plan would help ensure that ecologically valuable areas are zoned appropriately. In addition, the government should institutionalize UGS performance indicators within TOD planning to guide zoning decisions based on measurable environmental benefits. In light of the considerable ecosystem service value provided by UGS, it is essential for Jakarta's TOD framework ought to officially incorporate vegetated idle lands by enhancing pertinent governance mechanisms and planning policies. This can include optimizing the floor area ratio bonus scheme under Gubernatorial Regulation No. 50 of 2021, which allows private developers additional building rights in exchange for green infrastructure contributions. Other mechanisms, such as land banking and green zoning overlays, could support the long-term conservation of key vegetated parcels. These tools would promote the conversion of unused land into effective and reachable green areas, consequently boosting urban climate resilience. This study is not without limitations. First, it focused solely on three TOD areas in Jakarta, which may not capture the full heterogeneity of TOD development across the city or in other urban contexts. Second, the valuation utilized fixed assumptions regarding input variables including land cover carbon coefficients, energy prices, and rainfall data, which may vary over time and across different locations. Third, the study did not include social and cultural dimensions of UGS value, such as health benefits, recreational use, or community identity, which are essential for holistic urban planning. The exclusion was made because the UGS ecosystem services examined in this study are focused on climate change mitigation, whereas cultural or recreational aspects fall under the category of cultural ecosystem services. Future studies need to tackle these limitations by broadening the analysis

to include additional TOD areas and integrating a more diverse array of ecosystem services, including biodiversity, recreation, and public health. Combining quantitative valuation with qualitative assessments—such as stakeholder interviews or participatory mapping—could provide a richer understanding of UGS functions and perceptions. Furthermore, the combination of future land use scenarios and climate forecasts in valuation models may enhance the predictive ability of of these studies. Research exploring financing models and institutional mechanisms for securing privately owned green space for public benefit would also be highly valuable for implementation.

AUTHOR CONTRIBUTIONS

H.Z. Fikri has contributed in preparing the manuscript, analyzing and interpreting the data, and preparing all the maps and figures. H.S. Hasibuan has contributed in supervising the first author, obtaining funding, analyzing the data, assisting administrative, technical, and material support. R. Setiowati, corresponding author, participated in the preparation of the manuscript, analyzing the data, and supervising the first author.

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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.

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ABBREVIATIONS

%	Percent
°C	Degree Celcius
BRIN	*Badan Riset dan Inovasi Nasional*/National Research and Innovation Agency
BRT	Bus rapid transit
CO_2	Carbon dioxide
DKI	*Daerah Khusus Ibukota*/Special Capital Region
FV	Future value
GFA	Gross floor area

GHG	Greenhouse gases
HMI	Heat mitigation index
h	Hour
InVEST	Integrated valuation of ecosystem services and tradeoffs
KAI	*Kereta Api Indonesia*/Indonesia Railway Company
kWh	Kilowatt-hour
LULC	Land use land cover
LRT	Light rail transit
m^3	Cubic meter
min.	Minute
MRT	Mass rapid transit
Mt	Metric ton
PV	Present value
SCC	Social cost of carbon
TOD	Transit-oriented development
UGS	Urban green spaces
UHI	Urban heat island
USD	United States Dollar

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CASE STUDY

Spatial and temporal variations in water quality trends concerning land use dynamics and environmental management

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ABSTRACT

BACKGROUND AND OBJECTIVES: Water quality is a major global environmental concern because the impact of land use changes on water quality is usually studied by analyzing the relationships between water quality and land use indicators. Jordan is among the countries with the most limited water resources, grappling with climate change, increasing pressure from groundwater depletion, and a rising population. This situation calls for immediate action and sustainable water management. This study aims to assess spatial and temporal variations in water quality in northwestern Irbid between 2006 and 2023, as well as examining the impact of the land use dynamics and environmental management on water quality metrics and trends using geographic information system-based analysis.

METHODS: This study evaluated water quality changes in northwestern Irbid by analyzing selected physicochemical characteristics from several water source sampling sites for 2006 and 2023. These are electrical conductivity, calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulfate and nitrate. The analysis of spatial and temporal aspects was executed, leading to the classification of physicochemical water quality changes into improved, declined, or stable. Geographic information system-based analysis for spatial distribution and temporal changes was applied. The dynamics of land use changes and management were explored to propose the potential basic causes of the observed variations in water quality. This holistic approach supports the creation of data-informed water management strategies for the locality and delivers a detailed comprehension of water quality patterns.

FINDINGS: The findings indicate that the change concentrations of electrical conductivity, potassium, sodium, magnesium, bicarbonate sulfate and chloride are increased at several sites across the study area. In contrast, the concentrations of nitrate, sulfate, and calcium have diminished in specific locations. Notably, there is an improved change in water quality, due to the decrease of nitrate accounting for 93 percent of the overall area. Also, the electrical conductivity is 89.2 percent of the area experienced a rise in EC readings, indicating a decline in water quality. The observed trends in water quality could potentially be associated with recent alterations in land use, where urban growth and agricultural activities may have influenced pollution dynamics. Moreover, it may be associated with better management practices, implementation of effective environmental protection measures, which may influence by land use dynamics change and management.

CONCLUSION: The study was evaluated water quality variations in north-west Irbid governorate. It detects both advancements and declines, potentially influenced by alterations in land use and management dynamics, as well as natural and socioeconomic elements. Improved water quality indicates that proper water management measures may be implemented. The recommendations include land use planning, regular monitoring, and public awareness campaigns and stakeholder involvement. Future studies of water quality scenarios and risk evaluations must be part of long-term planning. Geographic Information System is an effective tool for mapping water quality trends and identifying hotspots, thereby supporting informed decision-making for sustainable water resource management.

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INTRODUCTION

Jordan has very limited water resources, with water usage across all sectors exceeding renewable quantities. Currently, the country extracts groundwater at a pace that is two times faster than its natural replenishment rate. Groundwater supplies approximately 70 percent (%) of the nation's domestic water and it serves as the primary source of drinking water, industrial, and agricultural needs. Projections regarding climate change imply a substantial decline in rainfall and a higher frequency of extreme drought situations. This will cause water stress, increase salinity, risk of contaminant intrusion, and decline recharge of aquifers and depth of water table and lead to further reductions in future renewable water resources (MWI 2022). In comparison to other regions globally, Jordan ranked as the second-poorest nation. For the year 2024, the anticipated water allocation is expected to be 73 cubic meters (m^3) per capita per year. Water quality is affected by a variety of natural and man-made factors and therefore, changes over time and across different locations. Consequently, it is important to keep track of and adjust water quality changes and develop maps to represent these variations, particularly in regions impacted by human actions. Here, the water quantity and quality are continually threatened by improper land use and pollution. Over the past four decades, numerous studies have been focused on the hydrochemistry, hydrogeology, and water quality in the northern region of Jordan (Kuisi *et al.,* 2009; Hillel *et al.,* 2015; Abboud 2018; Obeidat and Alawneh, 2019; Al-Addous *et al.,* 2023). Nonetheless, the demand to refresh these studies is on the rise, especially regarding water quality, owing to developments that have occurred over the past decade. These changes are largely driven by significant population growth and its wastes, agrochemicals, and introduction of new types of chemicals causing pollution. This study is also essential to evaluate the water quality evolution during the intensive socio-economic development of the last four decades. The Irbid governorate, situated in northern Jordan, serves as the focus of this study. This area is considered one of the more developed regions in Jordan. Also, it has an increase in urbanization, industry, commercial and agricultural activities. In addition, refugees resulting from the Syrian crisis (about 133,000 capita in the area) caused increasing pressure on the scarce water resources in quantity and quality. This governorate is a hot spot, mostly classified as of moderately vulnerable water resources (Alshoubaki and Harris, 2018; Breulmann *et al.,* 2022). Nonetheless, there is an ongoing shortage of extensive studies that evaluate water resources and water quality, along with their sustainability for drinking and agricultural applications. While several studies have examined specific water sources or areas within Irbid region, there are still problems of inadequate water supply and water quality in the area. Analyzing the variations in water quality in Irbid is essential for grasping how elements like pollution, urbanization, and climate change influence water resources as time progresses. This research adds value because it focuses on identifying changes over time, sources of contamination, and the long-term impacts on public health and the environment. It also highlights the effect of agricultural and socio-economic activities and local sources of contamination on water resources. Considering these facts, an extensive study was performed to analyze the changes in water quality over time and in various locations, with the goal of identifying potential hazard sources in the region that may influence water quality, such as wastewater, solid waste, and activities related to agriculture and industry. Modern computer-based technologies, including geographic information systems (GIS), offer a valuable decision support tool for mapping water quality variations and facilitating quick, reliable management decisions. The GIS is widely used for the assessment, monitoring, management, and visualization of geographic data across various fields, including natural resource management, environmental evaluations, disaster management, and hydrology (Chenini *et al.,* 2010; Lee *et al.,* 2012; Ramadas and Samantaray, 2018; Algailani and Hayder, 2025; Al Mahasneh *et al.,* 2025). By pinpointing areas with high pollution levels and observing trends, water quality maps establish a basis for future strategies and measures designed to safeguard public health, promote safe water usage, and mitigating environmental degradation. As a result, mapping water quality variations and hotpots is essential as it provides a clear spatial understanding of contamination patterns and affected areas, serving as a critical starting point for informed decision-making. It enables authorities to prioritize interventions, allocate resources efficiently, and design targeted strategies for monitoring,

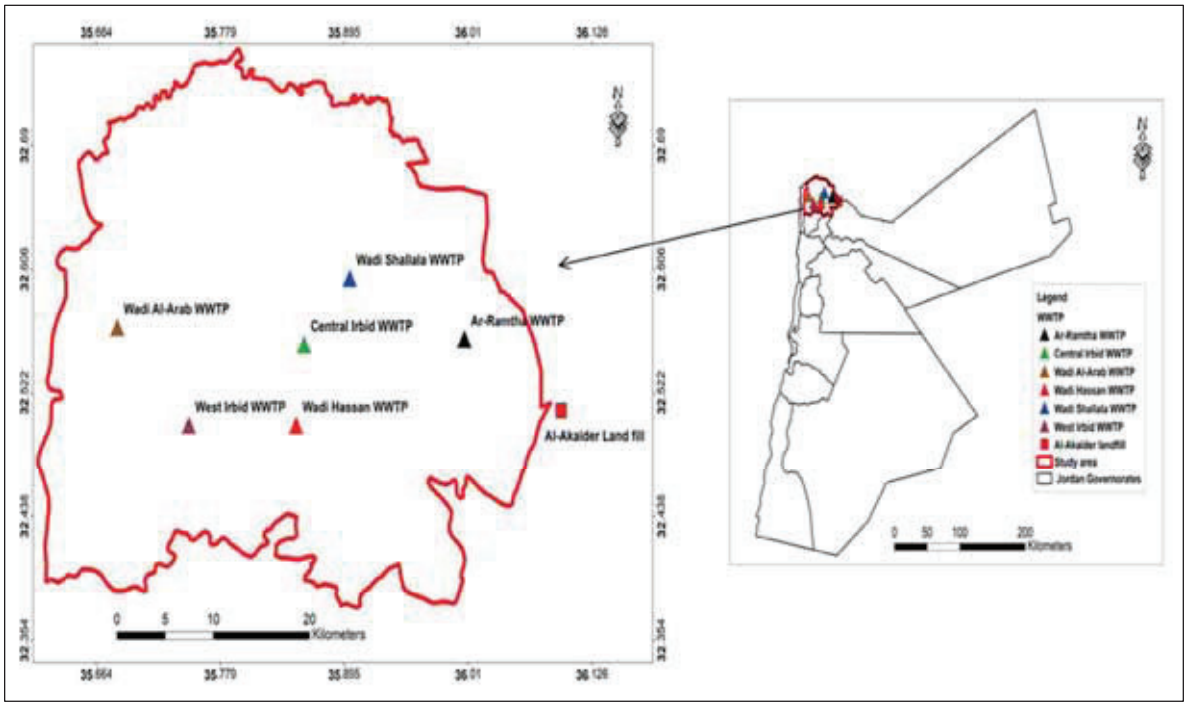

Fig. 1: Geographical location of the study area of waste water treatment plants and Al-Akidar landfill in Jordan

remediation, and sustainable water management. The current study tests the hypothesis that land use dynamics change and environmental management have altered water quality metrics and trends between 2006 and 2023 in the northwestern Irbid. The objective is to analyze variations in chosen physicochemical parameters of water quality through spatial and temporal assessments, recognizing changes in land use and management practices that may impact water quality trends, and assist in creating efficient local water management strategies. This study was conducted in 2023 in Irbid, Jordan

MATERIALS AND METHODS

Study area descriptions

This study is focused on the northwest (NW) parts of Irbid governorate, which is located in northern Jordan with a total area of 1,571.7 square kilometers (km^2) (Fig. 1). This area is defined by a semiarid climate, featuring hot summers and cold winters with significant rainfall. In 2025, it had around 2.1 million residents, making it the second most populated governorate after Amman. Roughly 133,000 Syrian refugees have entered the area as a consequence of the Syrian crisis, exacerbating the already insufficient water supplies in the region (Alshoubaki and Harris, 2018). Six wastewater treatment plants facilities (WWTPs) and the Al-Akidarlandfill point sources serve the region (Fig. 1). With the ability to process about 60,000 m^3 of wastewater per day, Irbid wastewater treatment plant is the biggest in the area.

This region exhibits a diverse topography, featuring elevation levels varying from under 200 meters (m) below sea level in the lower Yarmouk valley in the north, to roughly 1,300 m near Ajloun region in the south direction. In the eastern areas, elevations are around 700 m, while west of the highlands; they drop to below sea level. In the study area, the temperatures range from 22 degrees Celsius (°C) to 29°C in the summer, while 5°C to 9°C in the winter (Odat 2015) which is classified as semi-arid climate. It receives from 300 to 600 millimeters (mm) annual rainfall during winter season. In the study area, hydrology is shaped by rainfall and the landscape's topography. Surface water mainly comes from the springs of the Yarmouk River and seasonal wadis. The area contains both deep and shallow groundwater aquifers. Their recharges are influenced by topography, rainfall

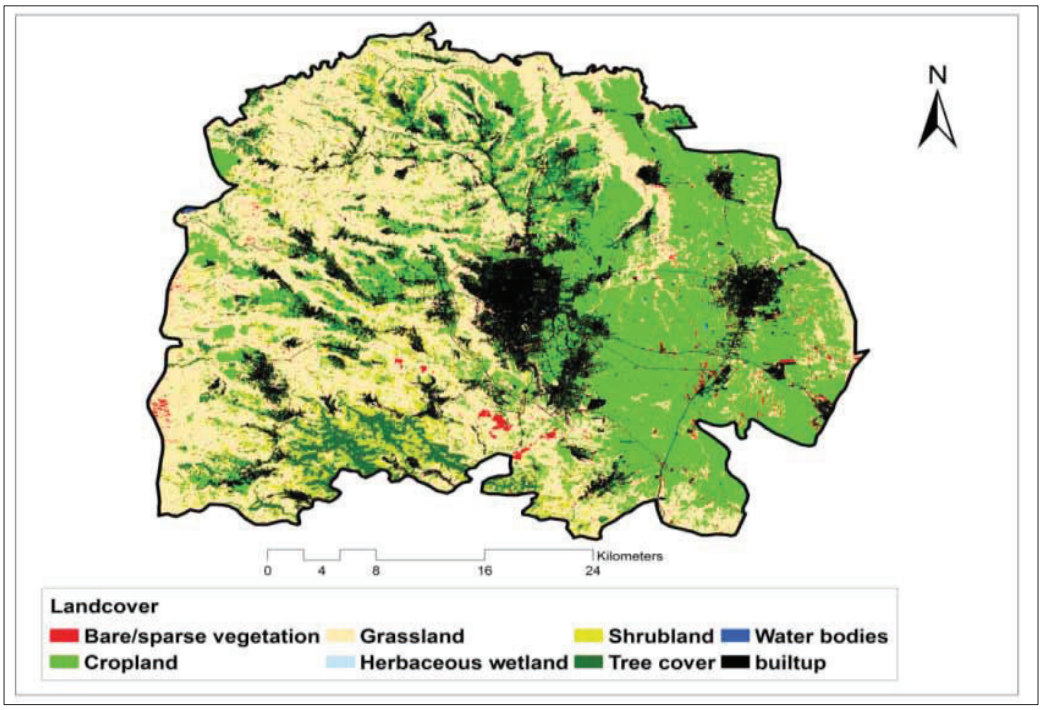

Fig. 2: Land cover and land use classification map (ESA, 2020)

and soil permeability. The soil texture on the gentle slopes varies from silty loam to loam, while in the valley bottoms, it is clay loam to loam. In addition, the permeability ranges from moderate to low in fine textured soils. The available aquifers are: Amman Wadi Es Sir B2/A7 aquifer located in northern Irbid alongside Umm Rijam and Wadi Shallala B4/B5. The tertiary aquifer system serves as the uppermost shallow aquifers which are contributing to local water resources of the area (Nawafleh *et al*., 2011; Abboud, 2018). Nonetheless, the efficiency of recharge is decreasing as a result of urbanization and alterations in land use. The study area has been posing a significant challenge for sustainable water management due to the climate and hydrology situation as well as the increase in human demand due to the increase in population growth and the refugee influx. All of them are causing over extraction and depletion of ground water. Wells and springs in the area are key sources of water resources. They significantly contribute to fulfilling both household and agricultural requirements. These water sources represent 80% of the total water supply. The land cover and land use (LCLU) map was extracted for the study area. The map derived based on the remote sensing data platforms (ESA, 2020). The classes are as follows: the dominant lands covering 43.2 % of the total area is used as grassland, while the cropland accounts for 28.50%, which indicates significant farming and agricultural activities. The urbanized areas (built up) represent 12.52%, reflecting a considerable extent of urban growth. Conversely, shrub lands cover 5.51%, and tree coverage stands at 8.58%, contributing positively to the biodiversity of the region. Water bodies take up a very small portion at 0.07% (Fig. 2).

Water quality assessment

Data collection, preparation and analysis

Water quality analysis was conducted by comparing two distinct time periods, spanning over 17 years' period. The historical dataset from 2006 was obtained from earlier studies, including academic theses (Nawafleh *et al*., 2011), while the most recent monitoring data from 2023 (or in some cases, 2022) were collected from the official records of the ministry of water and irrigation (MWI) in Jordan. Furthermore, specific datasets were acquired

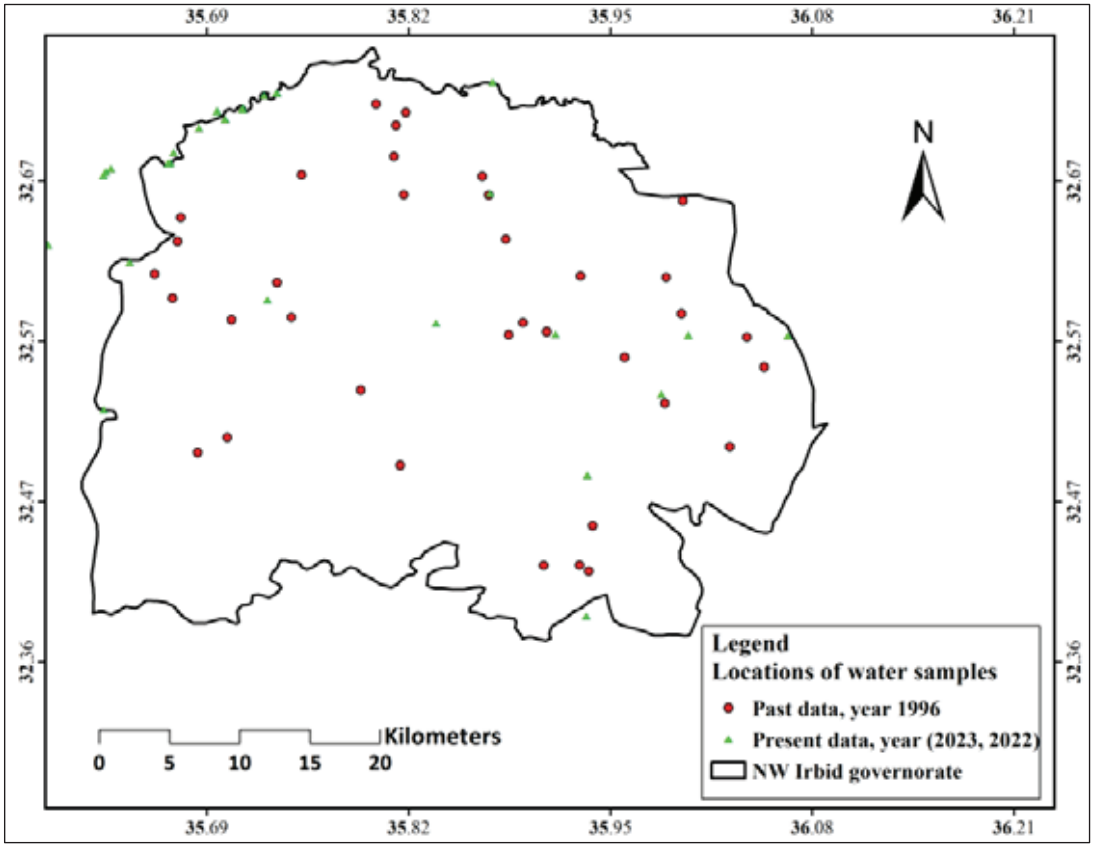

Fig. 3: Locations of water samples over 2006 and 2023

from the official publications of the royal scientific society (RSS). Additionally, samples obtained from the Mukhiebeh and Adasieya wells were examined in laboratories of the German federal ministry of education and research. Aspects have been evaluated concerning the nearness and consistency of sampling locations throughout the times. All samples were analyzed in accredited laboratories according to standard methods for the examination of water and wastewater, utilizing protocols from the American Public Health Association (APHA) and international organization for standardization (ISO) guidelines. This maintained consistency in sampling locations and techniques, and the data is adequately strong for comparative analysis. The datasets were collected on an annual basis for both periods. These were facilitated a thorough analysis of long-term water quality changes over the 17-year span. The water quality parameters under consideration included key cations and anions respectively (calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), chloride (Cl^{-}), sulfate (SO_4^{2-}), nitrate (NO_3^{-}) which were reported in milligram per liter (mg/L). Additionally, electrical conductivity (EC) was reported in microsiemens per centimeter (µS/cm), which serves as an indicator of overall ionic concentration and water salinity. Physicochemical information of the water quality metrics was collected from 40 and 30 sites for past (2006) and present (2023) periods, respectively. Among the numerous water sources collected in the study area were wells, springs, surface water bodies, wastewater treatment facilities, and dams. The geographic location of each sampling site was identified using east and north coordinate for both past and present study periods (Fig. 3).

The information of physicochemical water quality parameters is summarized to highlight temporal variations in key indicators such as EC, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, and NO_3^{-} for both the past

(2006) and present (2023) periods, Tables 1 and 2, respectively.

Summary statistics, including the minimum (min), maximum (max), mean, and standard deviation (SD) for each physicochemical water quality parameter during the past period (2006) and the present period (2023), are displayed in Tables 3 and 4, respectively.

GIS techniques were employed for geographical analysis. It facilitated the creation of spatial distribution of physical and chemical water characteristics datasets and mapping the changes over time. The locations of each sampling site were identified using easting and northing coordinates. The Easting and Northing coordinates of each sampling site were converted into GIS layers, which were then linked with their corresponding water quality data for spatial analysis and interpretation using ArcGIS software (version 10.8) (Esri, 2016). The datasets were arranged, and the measurement units were made consistent throughout the datasets. The GIS-based interpolation technique called inverse distance weighting (IDW) was used for mapping the spatial distribution of physicochemical water quality properties. The IDW estimates measurements by spatially interpolating data, where weights are assigned inversely proportional to the distance from known observation points to the prediction location. As a deterministic technique, IDW assigns more weight to nearby points, rendering it simple, rapid, and efficient for datasets characterized by sparse or uneven sample distribution. Importantly, it does not require complex statistical assumptions. In contrast, Kriging, which is a geostatistical approach utilizing a variogram to simulate spatial autocorrelation, resulted in excessively smooth surfaces and attributes that did not sufficiently capture the behavior of water

Table 1: Physicochemical water quality characteristics of the past period (2006)

Water source name	HCO_3^- (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^- (mg/L)	EC (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)	Na^+ (mg/L)
Rafad Farhan well	231.8	71.6	87.9	9.3	642	104.2	11.9	3.1	20
Nuaymeh 3	237.3	76.2	48.3	14.3	685	120.2	7.8	2	20
Nuaymeh Mun.1	205	42.9	96.1	2.5	553	110.2	10.5	1.2	20
Yarmouk univ. 1	280.7	76.2	101.1	80.6	621	108.2	45.3	2	20
Hassan ind. city	388.7	119.5	107.9	62	1310	104.2	9.4	5.9	129.9
Faleh Abu eshsheeh	410.6	100.3	108.9	40.3	1067	124.2	23.1	7	100
Ramtha Jabir highway No. 8	291.6	162.4	79.9	38.4	958	92.2	38.2	2	89.9
Ramtha custom	291	119.1	79.5	37.8	826	84.2	42.9	2	89.9
Mahasi 5	324	496.3	113.1	145.1	2600	124.2	76.3	25.8	289.9
Ahmad Elfandi	259.3	362.6	99.2	160	1776	110.2	49.8	3.9	239.8
Abdelraheem Ali'kour	194	167	89.3	117.2	1020	55.1	28.6	5.1	149.9
Musa Samarah	172.7	162.4	103.2	38.4	1122	100.2	23.8	2	100
Hareema 1	291.6	76.2	100	64.5	792	82.2	36.5	3.1	40
Hakama 3	302	71.6	92.7	71.3	804	93.4	41.2	3.1	49.9
Hakama 5	313	66.6	102.5	79.4	744	112.2	35.7	3.1	49.9
Hakama 6	302.6	76.2	79.5	87.4	733	104.2	31	3.1	60
Juhfiyeh no.1A	151.3	42.9	116.2	11.8	551	112.2	12.2	2	9.9
Tayyiba	291.6	47.9	99.4	1.9	644	88.2	24.2	2	29.9
Waleed Khazar	291.6	66.6	121.5	0	876	96.2	21.4	1.2	40
Jdeila No.1	183.6	76.2	66.1	96.1	732	100.2	28	3.1	29.9
Kufr asad 1	291.6	71.6	91.1	45.3	824	88.8	45.2	3.1	20
Wadi Alarab No.1	280.7	76.2	79.5	38.4	834	104.2	26.3	2	40
Wadi Alarab No.4	161.7	95.4	83.8	36	919	92.2	21.4	3.1	40
Wadi Alarab No.6	183.6	71.6	95.9	57.7	775	88.2	26.4	3.1	20
Refa'l Haznymeh	291.6	42.9	100.9	9.9	635	108.2	14.5	2	20
Douqara 1	237.3	47.9	51.4	13	552	100.4	21.4	1.2	9.9
Kufr Yuba	194.6	33.3	86.9	1.2	492	68.1	22.5	0	9.9
Deir Abu said	345.3	47.9	56.7	5	754	90.4	34	1.2	20
Deir Abu said spring	237.3	104.9	97.5	104.8	1117	114	16.5	7	80
Rahoub spring	227	66.6	104.7	73.8	575	76.2	31	2	40
Elkhureiba spring	324	47.9	100.9	96.1	638	79.2	51.8	5.1	20
Qweilbeh spring	205	42.9	85.6	70.1	504	64.1	47.3	2	9.9

Table 2: Physicochemical water quality characteristics of the present period (2023)

Water source name	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	EC (µS/cm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)	Na^+ (mg/L)
Outlet nafaq JV1	273	144	2.0	104.0	1063	72.0	34.0	7.0	91.0
Tabaria trans JV4	145	258	0.38	54.0	1170	45.0	32.0	7.0	124.0
Alarab dam JV2	152	213	0.42	81.0	1095	47.0	34.0	8.0	84.0
Sharhbeel dam JV202	234	57	0.79	46.0	644	43.0	38.0	4.0	32.0
Wehda dam JV0	212	127	2.06	119.0	979	40.0	36.0	7.0	98.0
Irbid WWTP1	700	332	0.49	120.0	768	101.0	38.0	53.0	241.0
Hakama No.9 well	315.8	109.7	<0.5	86.0	970	80.0	37.2	2.2	67.9
Huson deep well	308.7	41.4	31.1	15.5	632	75.9	25.4	2.3	23.0
Adasiah No.18 well	323.4	1138.8	3.8	1136.4	5530	187.2	215.4	74.3	719.6
Rahma AlKhateeb well	384.3	99.8	12.7	130.0	1154	116.5	34.6	8.0	67.8
Qweilbeh No.1well	338.4	47.7	24.3	28.0	763	103.4	16.0	3.7	30.0
Mahasi 5 well	433.9	323.8	114.4	97.6	2060	128.6	43.5	27.1	227.7
Jabir No.10 well	315.1	93.6	<0.5	41.5	861	72.1	32.4	1.0	57.4
Nuaymeh 4 well	294.2	52	55.7	16.5	773	77.0	29.2	6.2	28.0
Wasteyah qum 1 well	314.6	41.1	27.3	16.7	657	70.9	27.7	4.3	20.8
Meizar 3	280.51	324	<0.5	148	817	141.0	38.1	14.3	166.0
Meizar 2	275.44	67	<2.5	49.0	2200	75.8	25.8	4.16	49.9
Ein Reach	253.17	338	12.9	289.0	1799	169.0	38.5	25.1	212.0
Ein Makle	296.56	373	<2.5	159.0	1996	148.0	38.7	16.4	190.0
Ein Sahina	308.40	84	1.8	64.0	963	103.0	33.4	4.29	54.8
King Abdullah Canal	365.08	141	7.4	108.0	1162	89.1	34.4	9.15	95.7
Hima Spring Duke	305.10	209	<2.5	177.0	1492	124	33.9	18.7	121.0
Mukheibeh 9	579.69	86	<2.5	89.0	1251	60.7	33.3	18.8	148.0
Yarmouk Mu 9	265.19	121	11.1	106.0	1096	83.0	37.2	8.97	97.5
Mukheibeh 8	309.25	71	<2.5	66.0	764	67.8	20.6	6.36	63.5
Mukheibeh 2	385.22	61	<2.5	62.0	876	99.9	33.5	3.71	44.4
Mulkheibeh 13	336.83	64	<2.5	57.0	821	82.3	27.2	4.39	51.4
Mukheibeh 7	332.93	65	<2.5	57	815	82.5	29.0	4.5	52.1
Mukheibeh Y	332.56	66	10.0	41	808	83.5	27.7	4.51	53.3
Mukheibeh 4	380.28	61	<0.5	63	873	100	33.4	3.36	43.5

Table 3: Summary statistics of water quality parameters for the past period (2006)

Parameter	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	EC (µS/cm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)	Na^+ (mg/L)
Min	140.3	33.3	<0.5	48.3	458.0	55.1	7.8	0.0	9.9
Max	410.6	496.3	549.90	116.2	2600.0	124.2	76.3	64.1	289.9
Mean	255.0	91.6	80.10	90.8	899.2	98.0	32.4	6.8	59.7
SD	65.2	103.1	97.60	15.8	486.6	17.6	16.4	12.9	63.1

Table 4: Summary statistics of water quality parameters for the present period (2023)

Parameter	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	EC (µS/cm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)
Min	145.0	41.1	0.0	15.5	632.0	40.0	16.0	20.8	1.0
Max	700.0	1138.8	114.4	1136.4	5530.0	187.2	215.4	719.6	74.3
Mean	325.0	173.7	11.1	120.9	1228.4	92.3	38.6	111.8	12.1
SD	105.2	206.5	22.7	196.7	900.8	35.3	33.3	128.4	15.5

in local contexts. Other advanced methods were also considered but found unsuitable due to risks of overfitting and less accurate representation of water quality data. Overall, compared to these methods, IDW demonstrated to be an accessible and accurate interpolation technique for this study (Amalraj and

Pius, 2017; Hossain *et al*., 2024; Ikechukwu 2017; Khazaa'lah *et al*., 2023; AlMahasneh *et al*., 2023). After conducting geostatistical analyses using both IDW and Kriging interpolation methods for collected datasets; the cross-validation results revealed that the root mean square error (RMSE) was lower for IDW than Kriging, indicating that it provided more accurate spatial predictions compared to Kriging for the given dataset (Njeban2018). To boost the clarity and comprehension of these alterations, the data was organized into specific categories, which simplifies the visualization of changes across various locations and timeframes. To measure how water quality changed between the two time points, a change detection analysis was performed. The difference in each parameter was calculated using Eq. 1.

Change = Present (2023) – Past (2006) (1)

In order to assess the degree of variability in water quality for every parameter being monitored, GIS techniques including raster model builder and subtraction were implemented. Three categories were created from the detected changes: no change, decrease, and increase in the concentration of each parameter. The level of the relevant parameter rose in regions where values increased, indicating a deterioration in water quality; conversely, a reduction in concentration signifies an enhancement in water quality. The class of no change was defined as stable areas where little to no change was seen over time. Then, area analyses for produced water quality change classes were calculated. Although of limited parameter coverage, insufficient historical data and variability in sampling time and frequency were limitations during data collection stage. Nevertheless, the application of standardized laboratory methods for analysis, along with GIS-based spatial analysis and earlier findings, was employed to manage these constraints.

RESULTS AND DISCUSSIONS

Physical parameters

Electrical conductivity (EC)

The EC of water serves as an indicator of its capacity to carry an electric current. The findings from 2006 demonstrate a broad spectrum of EC values among the various locations examined. The spectrum of EC values extended from 458 µS/cm to 2599 µS/cm. Conversely, the recent results showed EC values ranging from 632 to 2058 µS/cm. The current analyses show that 89.2% of the area had a rise in EC values, which was prevalent throughout the majority of the study area; the change indicates a decline in water quality. These values maybe related to the natural factors and properties of shallow aquifer and hence susceptible to contamination by wastewater from cesspools and wastewater treatment plant in the wells area. In addition to that, the impact of climate change could contribute to the increased ion concentrations, thus raising the EC values. Moreover, particularly the human-induced practices of over-extraction of groundwater may cause an increased concentration of dissolved salts, which further raises the EC (MWI, 2022). This results aligned by (Bajjali *et al.,* 2017; Khawajah *et al.,* 2023). Conversely, 10.7% of the region exhibited a reduction in EC values, particularly in specific sections of the east and northwest of Irbid. This could be linked to better water management strategies (for instance, the development of a sewerage system) or changes in water recharge and flow dynamics. Additionally, 0.1% of the area remained unchanged (Fig. 4).

Chemical parameters

Calcium (Ca^{+2})

The Ca^{+2} is present in all waters as Ca^{+2} and is readily dissolved from rocks rich in Ca^{+2} minerals, particularly as carbonate (CO_3^{2-}) and SO_4^{2-}, especially limestone and gypsum. The concentration of Ca^{+2} in natural water is determined by its geological source and the extent of the chemical weathering process. As the most prevalent alkaline earth dissolved cation in groundwater, it plays a key role in contributing to water hardness. High concentrations of Ca^{+2} reduce the utility of water for domestic use. Ca^{+2} is also an essential constituent of many igneous rock minerals. The most common forms of Ca^{+2} minerals in CO_3^{2-} sedimentary rocks are calcite, aragonite, dolomite, gypsum and anhydrite. In the study area, past Ca^{+2} concentration levels in water ranged from 55 mg/L to 124 mg/L, whereas, the current concentrations range from 40 mg/L to 165 mg/L. Over the two periods, an increase in calcium concentration was observed by 21.2 % in the eastern and middle parts of the study area, which was attributed to higher levels in the current period, while a decrease in the most parts was recorded by 76.8% of the total area. The

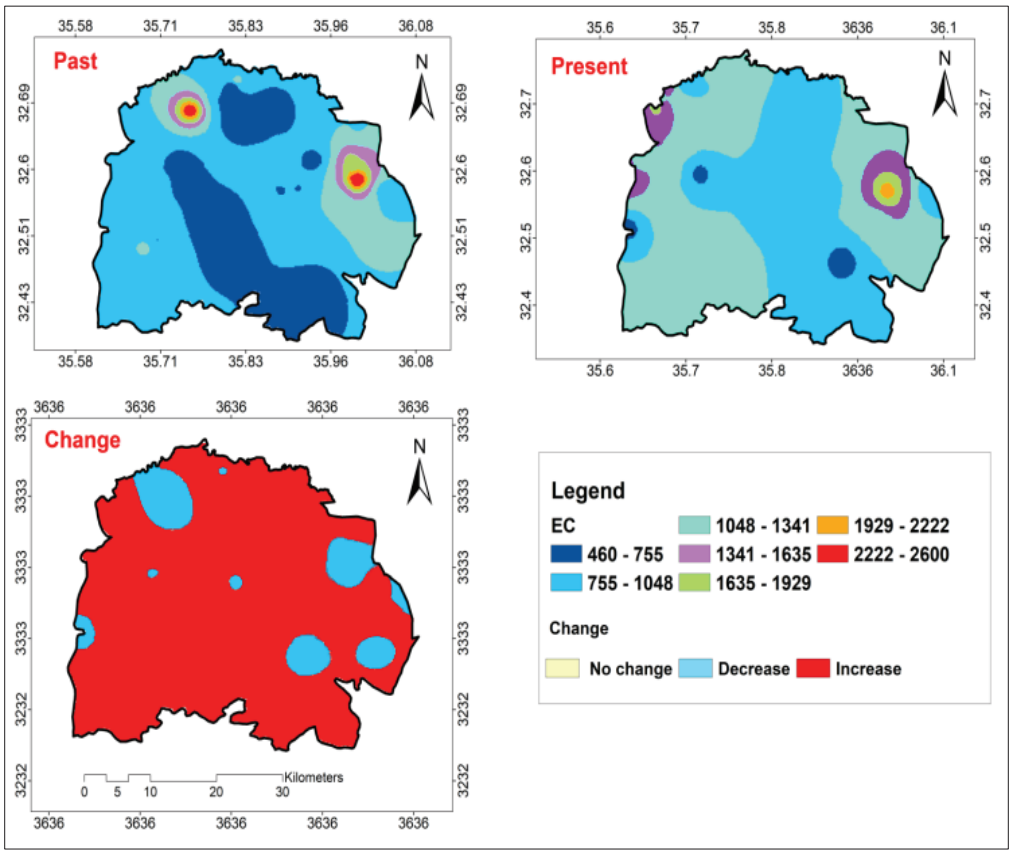

Fig. 4: Spatial and temporal changes in EC concentrations

last 2% exhibited no notable change, suggesting that geochemical conditions remained stable (Fig. 5).

Magnesium (Mg^{+2})

The Mg^{+2} is also one of the constituents causing water hardness and is generally found in lower concentrations than Ca^{+2}. Mg^{+2} is sourced from the weathering processes of igneous rocks that contain ferromagnesium minerals, as well as from CO_3^{2-} minerals in sedimentary rocks such as dolomite and magnesite (Lin *et al.,* 2022). A high quantity of Mg^{+2} reduces the utility of water for domestic use and also proves to be diuretic and laxative (Dupont and Hébert, 2020). From the initial results, it can be deduced that the Mg^{+2} concentration in most regions of the study area fluctuated between a minimum of 7.2 mg/L and a maximum of 76.3 mg/L. In the recent samples, Mg^{+2} concentrations ranged between 16 mg/L and 51 mg/L. Furthermore, Mg^{+2} concentrations is increased by 70.3 % in the most of lower middle parts in the study area, reflecting higher levels in the current period, while a decrease was observed in 27 % of the total area especially in the north western parts. The remaining 0.7% of the area exhibited no notable change in Mg^{+2} concentrations (Fig. 6). In contrast, certain regions, especially in the northwest, are facing a reduction in Mg^{+2} levels. A small part of the area demonstrated no remarkable change.

Sodium (Na^{+})

The natural Na^{+} content of water is essentially dependent upon the nature of the geology of the area and the weathering processes of rocks and soils (Lin *et al.,* 2022). The lowest recorded concentration of Na^{+} in the past was under 10 mg/L across different sites, while the highest was 289 mg/L. In contrast, the minimum current concentration was noted at 20 mg/L and the maximum at 240 mg/L. The highest Na^{+} levels were observed in Ramtha region, particularly near the wastewater treatment plant. In the current

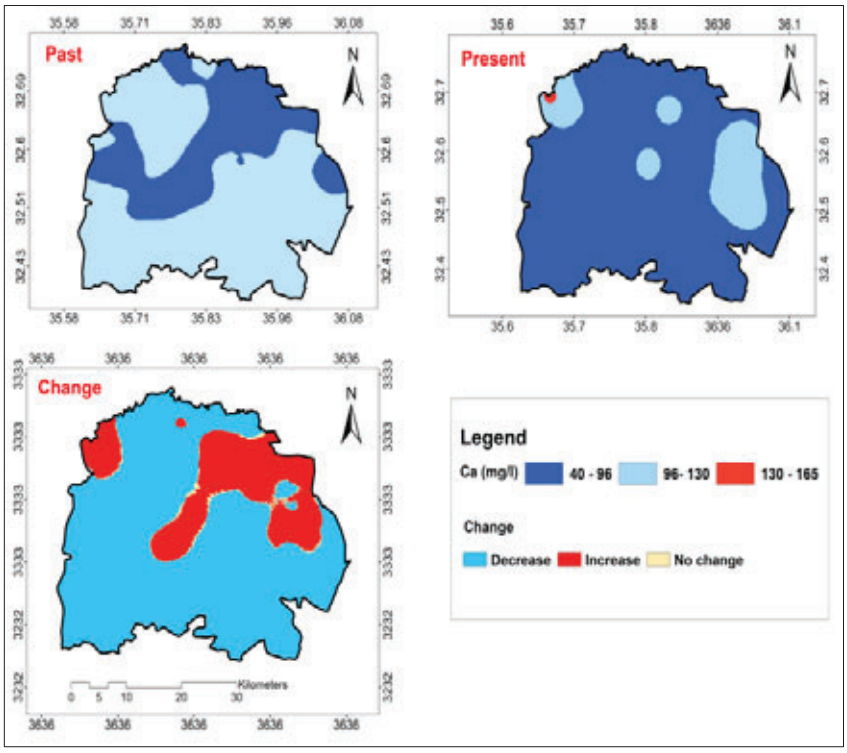

Fig. 5: Spatial and temporal changes in Ca^{+2} concentrations

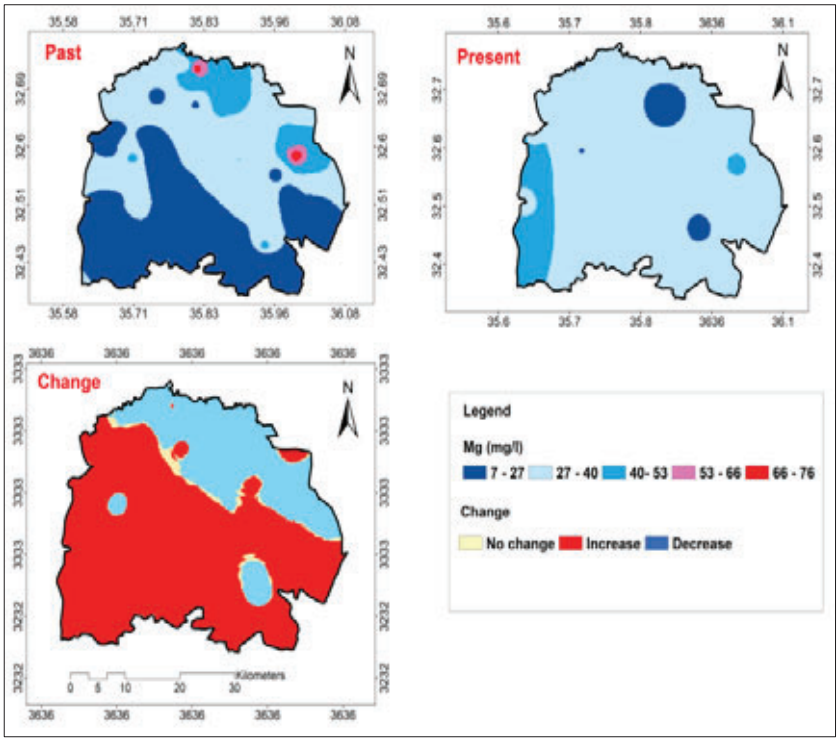

Fig. 6: Spatial and temporal changes in Mg^{+2} concentrations

period, Na^+ concentrations ranged between 15 mg/L and 245 mg/L additionally, its levels increased by (84.1%) in the majority of the study area, while a decrease was observed by 15.4% in the eastern part of the study area. The remaining 0.5 % of the area exhibited no notable change on its concentration (Fig. 7).

Potassium (K^+)

K^+ mainly originates from silicate minerals in igneous rocks and evaporates in sedimentary formations. Additionally, K^+ reaches groundwater via sewage discharges from industrial operations, agricultural practices, domestic wastewater, and improper wastewater management, especially in areas lacking proper management (Lin *et al.,* 2022). The past concentration ranged from 1 mg/L to 64.1 mg/L. In the current period, K^+ concentrations ranged between 1 mg/L and 52 mg/L, additionally, its levels increased in 87.2 % of the study area, reflecting higher concentrations, while a decrease was observed in 10.7 % of the total area. The remaining 2.1 % of the area showed no notable change (Fig. 8).

Bicarbonate (HCO_3^-)

The presence of CO_3^{2-} and HCO_3^- plays a role in determining the hardness and alkalinity of water. These ions exist in natural waters at different levels influenced by atmospheric, soil, and rock sources and the pH, temperature, and pressure conditions. The HCO_3^- ions result from the dissolution processes of carbonate rocks. The carbonate-carbon dioxide system plays a crucial role in regulating the presence of different CO_3^{2-}in water (Cherry and Freeze, 1979). The lowest past HCO_3^- concentration found in the study area was 140 mg/L, while the highest value was about 410 mg/L. In the current period, HCO_3^- concentrations ranged between 152 mg/L and 699 mg/L, additionally, HCO_3^- levels increased in 92.8% of the majority of study area, reflecting higher concentrations in the present period, while a decrease was observed in 2.6% of the total area. No significant changes were observed in the concentrations of the remaining 0.1% of the area (Fig. 9).

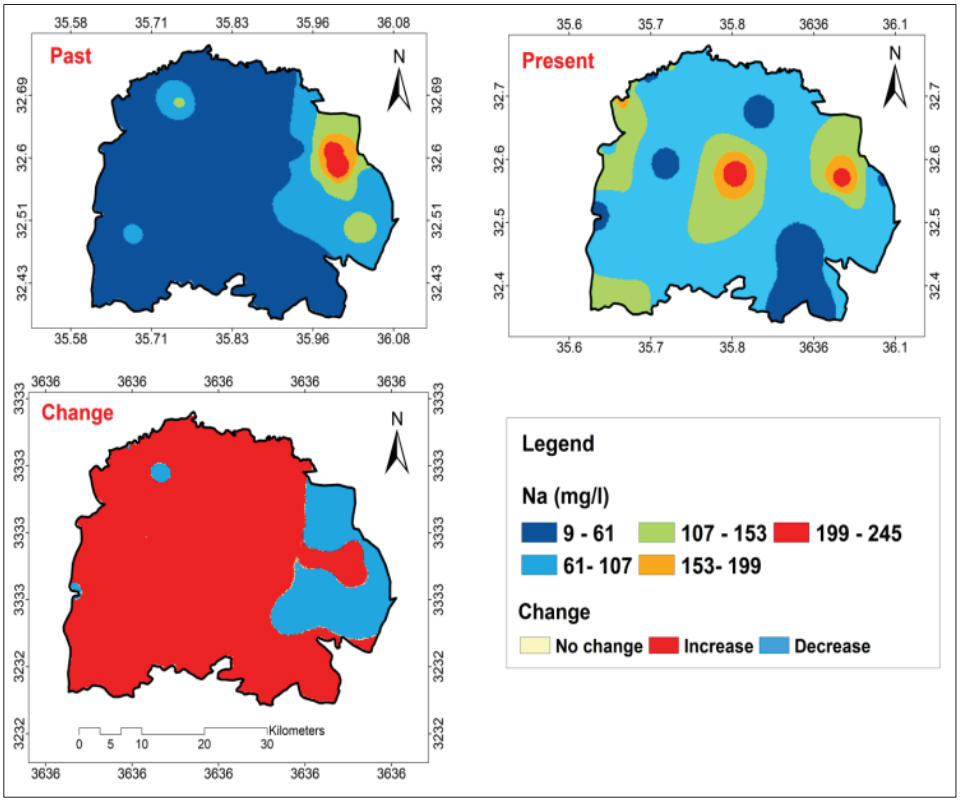

Fig. 7: Spatial and temporal changes in Na^+ concentrations

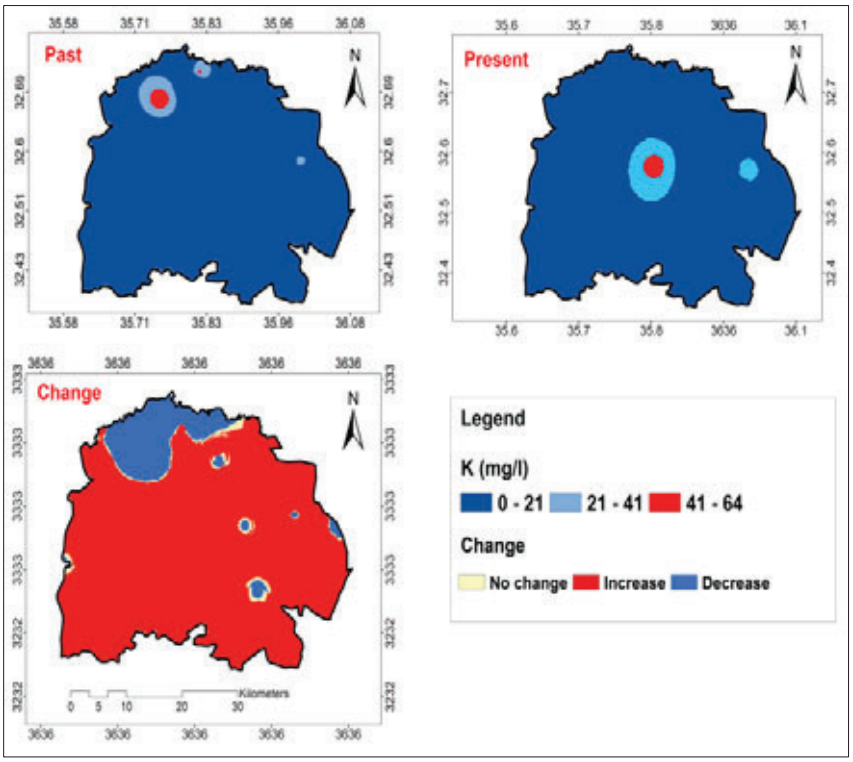

Fig. 8: Spatial and temporal changes in K^+ concentrations

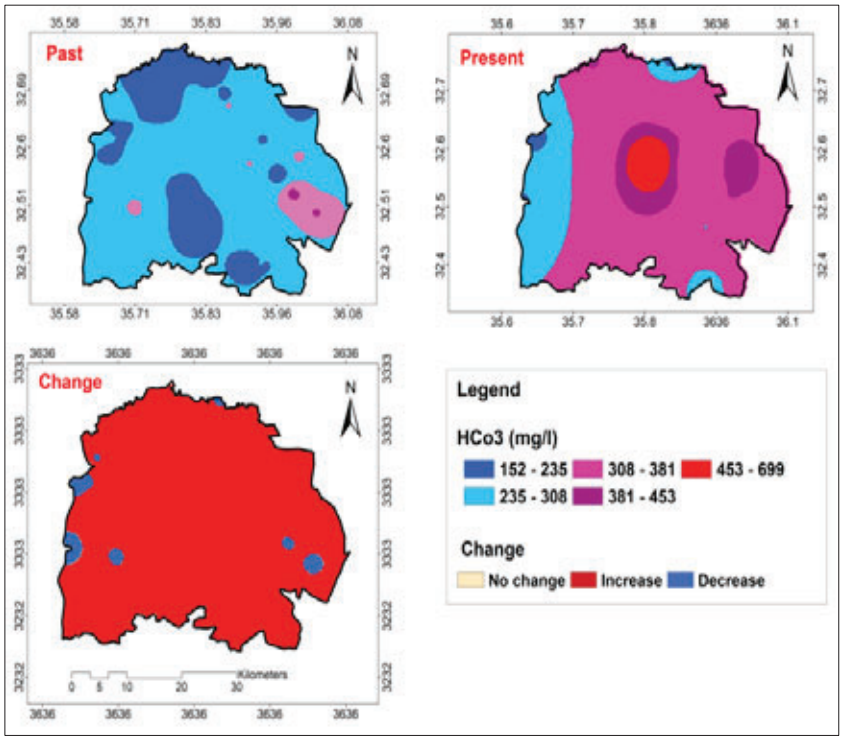

Fig. 9: Spatial and temporal changes in HCO_3^- concentrations

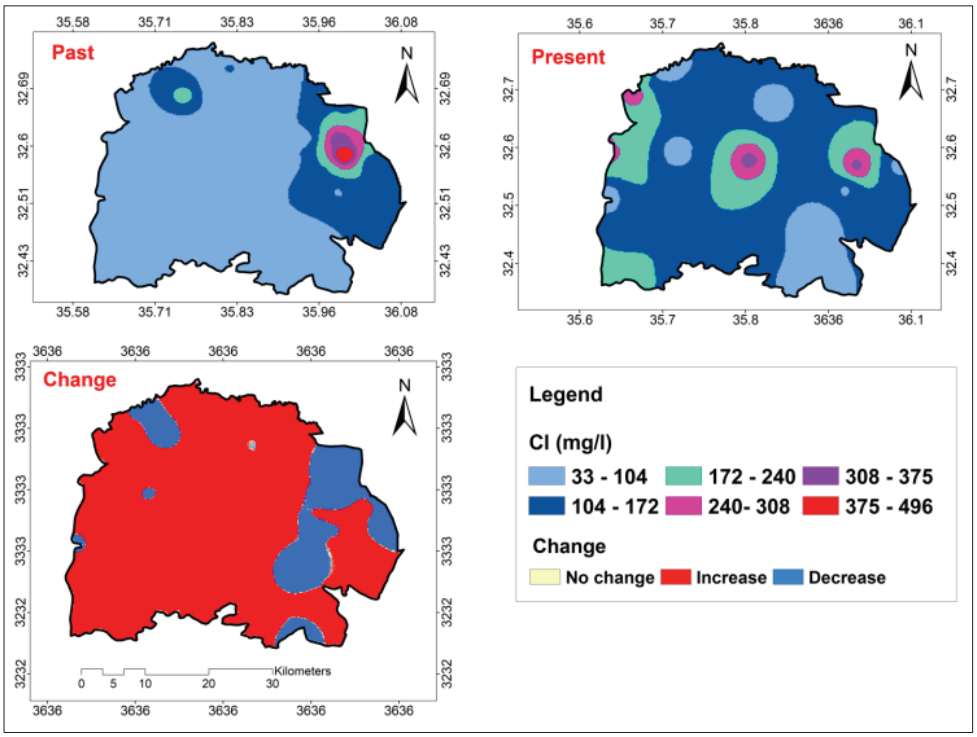

Fig. 10: Spatial and temporal changes in Cl^- concentrations

Chloride (Cl^-)

The occurrence of Cl^- in rock formations is generally small because it is readily solubilized and leached by water. The Cl^- content in fresh waters is usually less than HCO_3^- and SO_4^{2-}. Natural freshwater sources of Cl^- consist of evaporite rocks, organic materials from animals, and effluents from industrial activities. In the present period, Cl^- concentrations ranged from 41 mg/L to 352 mg/L. Additionally, its levels increased by 83.5% in the majority of the study area, indicating higher concentrations in the current period, while a decrease was observed in 15.9% of eastern part of the total area. The remaining 0.6 % of the area exhibited no notable change in its concentration (Fig. 10).

Sulphate ($SO4^{-2}$)

The SO_4^{2-} is found naturally in water, introduced through the leaching of evaporated rocks and soils, atmospheric precipitation, and from the discharge of domestic sewage and industrial effluents (Lin *et al.,* 2022). The SO_4^{2-} salts are mostly soluble in water and impart remnant hardness. The most common of SO_4^{2-} bearing minerals are gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$). These minerals dissolve readily when in contact with water. The dissolution reaction for gypsum is presented using Eq. 2 (Cherry and Freeze, 1979):

$$CaSO_4{\cdot}2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \quad (2)$$

The SO_4^{2-} concentrations ranged from about 48 mg/L to around 496 mg/L. In the current period, its concentrations ranged from 15 mg/L to 268 mg/L. Furthermore, there was a rise in levels in 48.9% of the northern and southeastern of the study area, reflecting higher concentrations during the current period, whereas a reduction of 49.4% was recorded in the northern and southeastern parts of the entire area. The remaining 1.7% of the area exhibited no significant change in SO_4^{2-} concentrations (Fig. 11). The thermal springs in the area produce water with high hydrogen sulfide (H_2S) gas, which leaks up along joints and fissures in the rocks and becomes dissolved in the shallow aquifer water. Moreover, high concentrations of $SO4^{2-}$ in spring sites may be associated with the infiltration of domestic wastewater in those area.

Nitrate (NO_3^-)

The NO_3^- represents the most oxidized state of nitrogen, and its elevated levels in water serve as a sign of pollution. Domestic and industrial wastewater including leaching from waste disposal sites and the use of inorganic NO_3^- fertilizers are the main sources of water pollution by NO_3^- (Craswell, 2021). In the current period, NO_3^- concentrations were dominated by less than (<) 47 mg/L while minor areas reached the class greater than (>) 47 mg/L to 114 mg/L. Generally, the highest NO_3^- concentrations were > 50 mg/L. Which is highly could be influenced by the infiltration of domestic wastewater from cesspools and agricultural activities in those regions. The NO_3^- concentrations increase towards some areas in south as shown in the spatial distribution map (Fig. 12). Furthermore, the NO_3^- concentrations have fallen by 93% across most of the study area, signifying lower concentrations in the current period, whereas a small rise of 6.6% was noted in the eastern region of the study area. The remaining 0.4% of the area exhibited no notable change (Fig. 12).

In particular, satellite-based estimates show that the region's built-up (urban) areas expanded by about 20% from 2000 to 2010, and by an additional 8% from 2010 to 2020 (Sahwan *et al.*, 2022) (Fig. 13). The notable changes in land use during the last two decades might have led to a decline in its levels in some areas. This decrease could be associated with the enhanced water quality noted in certain regions of the study area.

Furthermore, the increase in population and the influx of Syrian refugees have led to significant growth in urban areas, encroaching upon agricultural land in certain regions and altering the patterns of surface runoff. Moreover, water resource protection zones under national projects may help to safeguard water quality, as have government-led upgrades to wastewater treatment infrastructure, such as the extension of WWTP networks that serve more than 60% of northern Jordan's urban populations (MWI 2019). As a result of improvements in treatment quality and effluent standards, the wastewater treatment capacity in Irbid has increased from

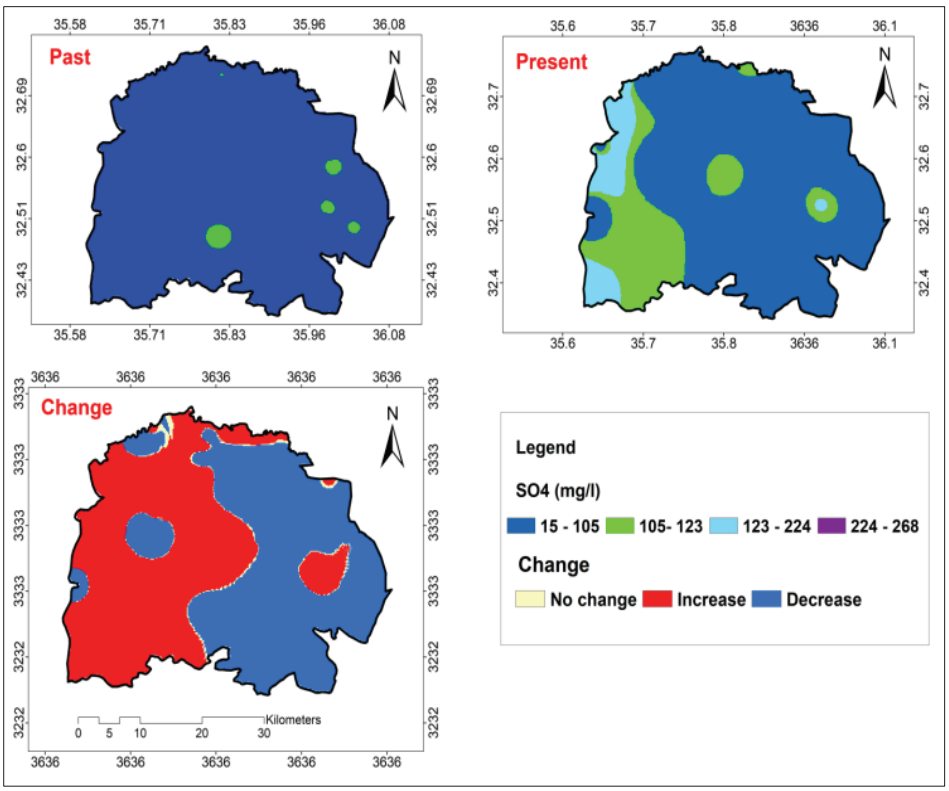

Fig. 11: Spatial and temporal changes in SO_4^{2-} concentrations

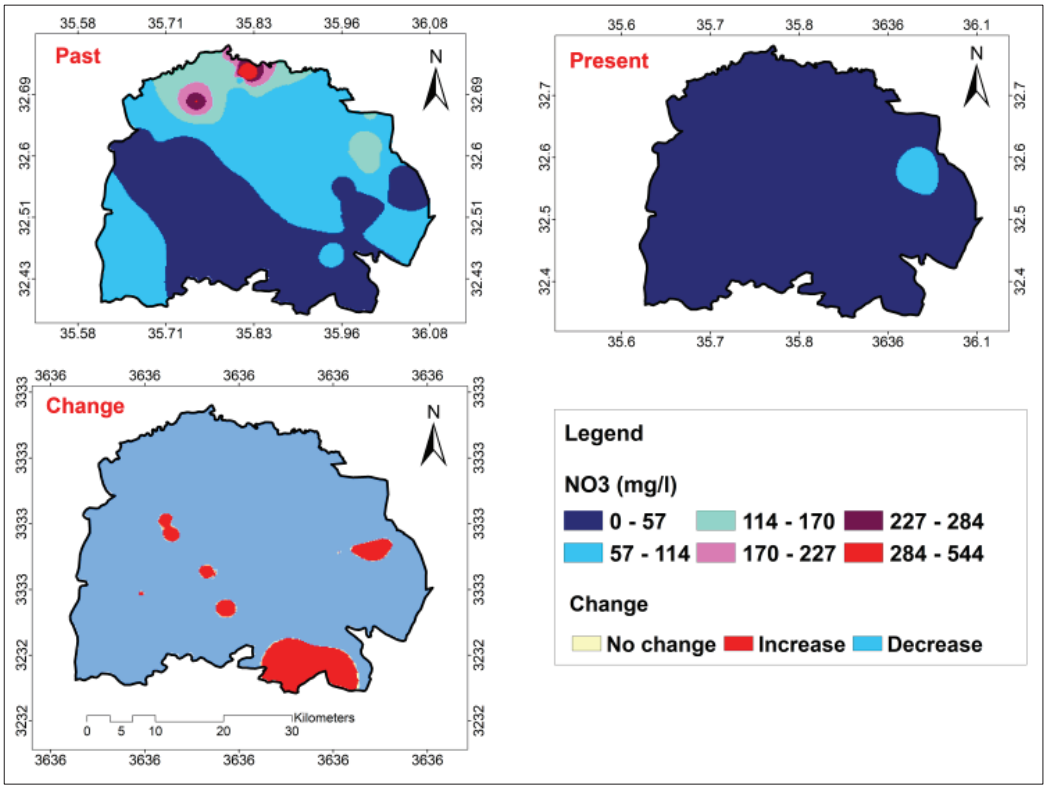

Fig. 12: Spatial and temporal changes in NO_3^- concentrations

approximately two facilities to six since 2006. This improvement has lowered the pollution impact of cesspools in the region and could potentially enhance groundwater quality by decreasing the discharge of contaminants. Furthermore, enhancements elevating treatment quality and effluent standards may cause reduce in contaminants in treated water by up to 30% as stated by (Alshogoor *et al.,* 2022). For instance, soil nitrate an example of diffuse agricultural pollutants, and may be decreased. These elements could clarify the reasons behind the enhanced water quality that has been reported. Conversely, it is likely that new pollutants have infiltrated the environment due to the swift urbanization and growth of industrial activities and chemical industries, potentially leading to water contaminants such as organic compounds, salts, and heavy metals (Rashmi, 2020; Khawajah *et al.,* 2023). As a result, the localized drops in water quality may result from these developments, particularly in unregulated urban areas. Moreover, Surface runoff significantly affects the quality of surface water through several mechanisms. Consequently, despite improvements in infrastructure, these human-induced effects could result in negative consequences and deterioration in water quality, potentially negating the advantages of enhanced water quality (Sahwan *et al.,* 2022). The worsen change in water due the increasing concentrations of the key parameters (e.g. EC, Na^+, Cl^-, NO_3^-, SO_4^{2-}) indicated to the high salinity of water and pollution in specific cases (Bajjali *et al.,* 2017). This affected its potential suitability for different uses such as drinking, domestic and agricultural uses. Their adverse implications on the public health and crop productions were documented by (FAO, 1985; WHO, 2017). Consequently, these variations have led to considerable effects on local communities and have influenced agricultural production due to rising salinity levels and household water availability, particularly in light of climate change effects (FAO 2018; IPPC 2022). These changing use patterns are strongly related to the spatial trends identified in the research. Irrigation of agricultural zones could be additional reasons for groundwater over-extraction, and declining water levels and cause salinity accumulation. Moreover, increased concentrations of NO_3^-, K^+, EC could be affected by irrigation return

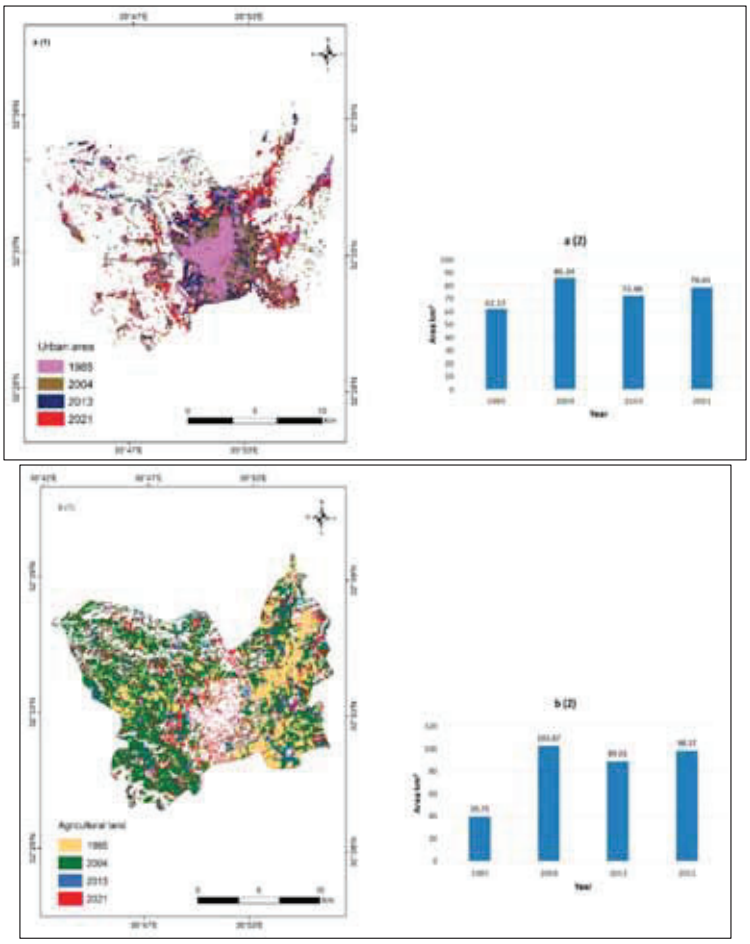

Fig. 13: (a1) urban extent; (a2) the area of the urban area over the study period from 1985–2021; (b1) agricultural land extent growth; (b2) the area of agricultural land over the study period (1985–2021) (Alshogoor *et al.,* 2022)

flows where excess fertilizers and dissolved salts leach back into the aquifer which summarized by (MWI 2022). The socio-economic influences could be associated with over-extraction of water and aggressive farming practices, such as the excessive application of fertilizers and irrigation, which may elevate the risk of degradation.

CONCLUSION

The spatiotemporal assessment of water quality changes in the northwestern Irbid governorate has been thoroughly conducted. Physicochemical water quality parameters were measured at 70 sampling sites representing various water resource types across the study area. Spatial interpolation was applied to these concentrations to visualize distribution patterns and highlight potential areas of concern. Spatial distribution maps for the years 1996 and 2023 were generated, revealing notable improvements in some locations and declines in others. The study's findings reveal that changes in land use, especially the expansion of urban areas and modifications in agricultural practices, together with management actions, play a crucial role in affecting the spatial and temporal variations of water quality in the study area. Sustainable water resource management and protection of water quality require the integration of continuous monitoring, adaptive land use planning, and effective environmental management policies. This study provides an effective tool for mapping water quality hotspots, highlighting areas that require urgent and targeted management

interventions. Deterioration in water quality might jeopardize the adequacy of water for residential and farming needs, while recognized advancements emphasize the favorable outcomes of sound water management practices focused on avoiding contamination and decline. Furthermore, enhanced management and operation of solid waste, septic tanks, and sludge are critical. In many urban and rural areas, urgent expansion of sewerage networks and construction of new wastewater treatment facilities are needed, along with upgrading existing plants by incorporating advanced treatment technologies. Implementing robust regulations and policies with active stakeholder engagement is essential, as a core component of integrated water resources management. Furthermore, land use planning, ongoing water quality assessments, campaigns to raise public awareness, and strict enforcement of environmental laws are crucial for the preservation of water resources, public health, and the environment. Looking ahead, scenario analysis and risk assessment of future water quality conditions are necessary to support long-term planning. GIS serve as robust tools for the collection, manipulation, and mapping of geographic and descriptive data. GIS is effective in analyzing spatial and temporal variations in physicochemical water quality parameters. It also helps identify and map hazards and pollution trends. By facilitating comprehensive spatial and temporal analyses, GIS is capable of identifying pollution sources and showcase data in easily understandable visual formats. This significantly improves the evaluation of hydrochemistry and water quality. These capabilities allow stakeholders to evaluate different management strategies, prioritize areas for investment or protection, and develop flexible policies that balance sustainability goals with water demand. Consequently, the integration of GIS with advanced real-time monitoring systems in water quality monitoring initiatives. This integration enhances environmental strategies and policymaking and supports decision-makers in managing water resources sustainably.

AUTHOR CONTRIBUTIONS

M. Rahbeh the corresponding author, supervised the first author, conceived the research idea, contributed to data analysis, and reviewed. L. AlMahasneh conceived, designed, and conducted the research, as well as overseeing sample collection and acquisition of analytical measurements, analyzing the data, interpreting the results and maps, discussing the results, preparing manuscript draft and review, finalizing the manuscript. E. Salameh conceived the research idea and contributed to setting up the acquisition of measurements arrangements and data analysis discussion and revised the manuscript draft. S. Naoum revised the manuscript draft, coordinated the activities and assisted in the analytical measurements arrangements. D. Abuhamoor participated in interpreting the results and maps and revised the manuscript draft.

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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.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
+	Add
<	Less than
>	Greater than
→	Produce
APHP	American Public Health Association
Ca^{2+}	Calcium
B2/A7	Amman Wadi Es Sir
B4/B5	Umm Rijam and Wadi Shallala
CO_3^{2-}	Carbonate
CaSO4.2H2O	Calcium sulfate dihydrate
Cl^-	Chloride
EC	Electrical conductivity
e.g.	For example
Eq.	Equation
ESA	European space agency
Esri	Environmental systems research institute
FAO	Food and agriculture organization
GIS	Geographic information system
GmbH-UFZ	Helmholtz centre for environmental research
H3	Anabin Database
H_2O	Water
HCO_3^-	Bicarbonate
H_2S	Hydrogen sulfide
IDW	Inverse distance weighting
Ind.	Industrial
IPCC	Intergovernmental panel on climate change
ISO	International organization for standardization
JV	Jordan valley
K^+	Potassium
Km^2	Square kilometer
LCLU	Land cover and Land use
m	meter
m^3	Cubic meter
max	Maximum
min	Minimum
Mg^{2+}	Magnesium
mg/L	Milligram per liter
mm	Millimeter
Mun.	Municipality
MWI	Ministry of water and irrigation
Na^+	Sodium
NARC	National agricultural research center

NO_3^-	Nitrate
No.	Number
NW	Northwest
pH	Potential of Hydrogen
Ph.D.	Doctor of philosophy
RMSE	Root mean square error
RSS	Royal scientific society
SD	Standard deviation
SO_4^{2-}	Sulfate
Spatio	Spatial
µS/cm	Microsiemens per centimeter
Univ.	University
WWTPs	Wastewater treatment plants

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CASE STUDY

Land use change and effects on carbon emissions using the logarithmic mean divisia index

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ABSTRACT

BACKGROUND AND OBJECTIVES: Urbanization continues to rise in urban centers and cities worldwide, particularly in developing countries. As the second-largest tourist destination and education hub in Indonesia, Yogyakarta Province is experiencing unprecedented population growth, which is further accelerating changes in land use and resulting in a significant increase in carbon emissions over the past few decades. Lacking proper management, this trend may endanger the environmental viability and livability of its territories. The study objectives were to examine the effects of land use on carbon emissions in Yogyakarta Province from 2000 to 2023 by decomposing the determining factors—land use change, economic development, energy structure, energy efficiency, and population—and analyzing the contributions of each to carbon emissions. This study is distinctive because it takes into account the multifaceted elements that impact carbon emissions, as opposed to prior studies that usually focused on a single aspect.

METHODS: To achieve this goal, the study employed the logarithmic mean divisia index, a decomposition method that has been widely used in carbon-related studies due to its residual-free nature, completeness, ease of operation, and applicability. Data pertaining to the province's carbon emissions associated with land use, including their designated sectors—agriculture, transportation, households, businesses, general use, industry, and industrial processes and product use—were collected from government agencies throughout the study periods. In contrast, the coefficients for carbon emission factors were retrieved from the Intergovernmental Panel on Climate Change emission factor database. The complex formula for calculating carbon emission intensity and decomposing the determining factors followed the Intergovernmental Panel on Climate Change guidelines and seminal studies using the logarithmic mean divisia index method.

FINDINGS: Key findings reveal that the industry, the households, business, and general use, and the industrial processes and product use are the three economic sectors that significantly contribute to carbon intensity in the province. The study employed the logarithmic mean divisia index to break down the variations in carbon emissions, revealing the influences behind their rise. The primary factors identified were land use change, economic development, and energy structure.

CONCLUSION: This study advocates for approaches to mitigate carbon emissions, including the integration of renewable energy and clean technologies, the establishment of carbon incentives, and the implementation of sustainable land use, transportation, and waste management in the province's future development.

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94	10	5

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INTRODUCTION

Increased social and economic prospects, improved access to political participation, and improved public infrastructure are crucial factors influencing migration to urban areas (Hanberry, 2020). Consequently, the global urban population is expected to grow significantly, rising from its current level of approximately 55 percent (%) (4.4 billion people) to 70% by 2050 (United Nations, 2025a, 2025b; Venditti, 2022). It is anticipated that this trend will endure, especially in Asia and Africa, leading to substantial strain on the global environment. The impacts of population growth include reduced biodiversity (Zipperer *et al*., 2020), changes in ecological interactions (Theodorou, 2022), and increased vulnerability to hazards (Bikis *et al.,* 2025) and pollution (Zhang and Cai, 2022). In numerous developing countries, the fast-paced growth is projected to induce major transformations in land use and land cover (Bikis *et al*., 2025; Hanberry, 2020), with land expansion reportedly surpassing the rate of population growth. Land expansion often results from the enlargement of cities' boundaries through processes such as agglomeration, stemming from either compact urban planning or urban sprawl (Hanberry, 2020). Urban land is projected to increase by 1.8-5.9 times, with per capita land use rising by 1.1-4.9 across various socio-economic scenarios throughout the 21st century (Gao and Neill, 2020). Such modifications may give rise in significant issues, including the formation of slums, a decline in urban green spaces, and the exacerbation of urban heat islands (Chen *et al.,* 2022). Additionally, industrial expansion linked to urban sprawl can result in higher energy consumption and increased carbon emissions. Furthermore, the decentralized and polycentric frameworks of cities might foster the use of personal vehicles, thereby intensifying carbon emission rates (Kakar and Prasad, 2020; Lyu *et al*., 2025), potentially leading to a range of health concerns (Rizaldi *et al.,* 2022). Cities play a critical role in shaping the future of global living. They account for two-thirds of global energy consumption and contribute to over 70% of greenhouse gas (GHG) emissions (United Nations, 2025b). GHG is a major factor influencing climate change, with carbon dioxide (CO_2) responsible for approximately 73.5% of total emissions (Filonchyk *et al.,* 2024), along with methane (CH_4) and nitrous oxide (N_2O) (Bhatti *et al*., 2024). These GHG emissions are intricately connected to human actions, particularly the significant reliance on fossil fuels for energy production, industrial operations, transport, and farming. Based on their energy sources, those activities are categorized into industrial and household sectors, which rely on electricity, gas, transportation, and heating (Clift and Druckman, 2015; Liu *et al*., 2020). Moreover, land use modifications, biomass combustion, and waste management, alongside human actions, significantly impact GHG emissions (Lyu *et al.,* 2025). Regarding land use changes, primarily forced by deforestation, they account for approximately 10-15% of total GHG emissions. When trees are cleared for cropland or urban areas, the carbon stored in trees and soil is released into the atmosphere as CO_2 (Wang, 2024). Additionally, the burning of biomass and tilling of soil (Foley *et al*., 2005) also release CH_4 and N_2O. In various instances worldwide a positive relationship between land use changes and GHG emissions has been noted, particularly in Africa, (Maccarthy *et al*., 2018; Wachiye *et al.,* 2020), as well as in Australia (Andrews *et al*., 2021), Europe (De Lotto *et al*., 2024), and Asia (Ahmed *et al.,* 2025; Huang and Li, 2022; Muga *et al.,* 2025; Raihan *et al.,* 2022; Yuan *et al.,* 2024). China has been notably emphasized in studies because of its vast population and emissions linked to agriculture (Ahmed *et al.*, 2025). Other nations that played major roles in global emissions and are central to research are the USA (15%), the EU (9%), and India (7%), with respective emission rates of 2.8%, 2.1%, and 0.8% (Friedlingstein *et al*., 2020). In Asia, Indonesia ranks as the third-largest emitter, following China and India, particularly in the energy sector, which heavily relies on liquefied petroleum gas (LPG), liquefied gas for vehicles (LGV), natural gas (NG), and liquefied natural gas (LNG) (Herlina *et al*., 2025). However, empirical research examining the effects of land-use changes on GHG emissions in Southeast Asia (SEA) and Indonesia, along with their associated factors, is limited. A majority of studies often emphasizes a narrow focus, frequently examining just one or two emission factors. These studies typically analyze the dynamics of urban green spaces (Agustiyara *et al.,* 2025), factors driving household energy consumption (Sudarmaji *et al*., 2022), historical emissions based on consumption and production (Rum *et al.*, 2024), as well as the consequences of land use changes on water quality

(Brontowiyono *et al.,* 2022). Moreover, most of those studies were performed at a scale broader than a province (Khusna and Kusumawardani, 2021; Amheka *et al.,* 2022; Huang *et al.,* 2025; Kim *et al.,* 2025; Lisaba and Lopez, 2021; Zhang *et al*., 2020) and concerned with the aggregate level, such as energy efficiency (Sudarmaji *et al.,* 2022, 2024). Different strategies have been utilized to investigate the links between energy consumption, land use, and GHG emissions. As an illustration, Structural Equation Models Optimization in Python was applied to quantify how land use affects emissions (Li *et al.,* 2024). Additionally, spatial autocorrelation analysis was utilized to uncover the relationships between demographic factors, territory, and emissions (De Lotto *et al*., 2024). The integrated linear and non-linear autoregressive distributed lag (ARDL and NARDL) models were used to illustrate the dynamic effects of significant agricultural key variables on emissions (Ahmed *et al.,* 2025). Moreover, the integrated standard deviation ellipse and geographically and temporally weighted regressions (GTWR) models were employed to identify the impacts of land use change on emissions (Yuan *et al.,* 2024). the combined bounds testing ARDL and the Dynamic Ordinary Least Squares (DOLS) method to investigate the nexus among energy use, agricultural land expansion, deforestation, and emissions (Raihan *et al.,* 2022). Finally, the logarithmic mean divisia index (LMDI) model was used to analyze the factors driving total emissions (Ang, 2004, 2005; Sudarmaji *et al.*, 2022; Wang, 2024; Zhao *et al.,* 2021). LMDI is particularly effective in examining factors influencing energy consumption growth, such as transportation (Tu *et al.*, 2019), coal consumption (Chong *et al*., 2015), energy consumption (Kim, 2017), and land use changes (Zhao *et al*., 2021). For instance, Zhao (2021) reported a significant increase in carbon emissions—approximately 16.71 times—resulting from land use changes between 1990 and 2015, with emissions concentrated in specific areas of the Pearl River Delta in China (Zhao *et al.,* 2021). By integrating with particular approaches, LMDI can assist in a deeper examination of the interactions between elements that impact carbon emissions through scenario models. For example, Chen *et al*. (2021) combined LMDI with a bootstrap approach to assess the influence of interactions between multiple factors on energy consumption in China from 1997 to 2017 (Chen *et al*., 2021). Initially presented by Ang (2004), LMDI provided a more straightforward decomposition and enhanced adaptability in different data analyses (Ang, 2005). Additionally, the method can meet the factor-reversal test and produces no unexplained residuals (Kim, 2017), making it applicable and easy to operate (Jiang *et al.*, 2023). This study employs the LMDI technique to investigate how land use has influenced carbon emissions in Yogyakarta Province over the past decades (2000-2023). Yogyakarta Province, situated on Java—Indonesia's most densely populated island—is undergoing swift urbanization, leading to considerable alterations in land use, such as the transformation of green spaces to gray infrastructure and impermeable surfaces (Arif and Toersilowati, 2024). Between 1992 and 2009, urban sprawl led to a notable decline in farmland (Shrestha, 2013). A governmental report indicated a 4.72% decrease in rice harvest area in 2023 compared to 2022, resulting in lower rice production (BPS DIY, 2024d). Urbanization has also resulted in higher GHG emissions, with the agricultural sector responsible for roughly 24% in 2019—a trend that is projected to keep increasing (UGM, 2019). Indonesia aims to reduce GHG emissions by 41% under an international support scenario by 2030. At the policy level, the government has enacted regulatory frameworks, including Law No. 16/2016 in response to the Paris Agreement and the United Nations Framework Convention on Climate Change, Presidential Regulation No. 18/2020 as part of the 2020-2024 National Medium Term Development Plan, and Presidential Regulation No. 98/2021, which sets emissions reduction targets at the provincial level (Rum *et al.,* 2024). In Yogyakarta, the authorities have backed initiatives to reduce emissions by controlling emissions, boosting capacity via research partnerships and innovation, and enforcing a range of regulations. For instance, the governor issued the Province of Yogyakarta Law No. 30/2007 to foster collaborations toward an energy-efficient master plan and renewable energy, aiming to reduce emissions (ICLEI, 2013). This initiative included regulations No. 39/2010 concerning gas emissions from motorized vehicles and No. 83/2024 concerning the development of a green city. In spite of these initiatives, GHG emissions continue to be a significant issue, especially as a result of tourism's effects (Saputra *et al*., 2013). This study aims to examine the effects of land use on carbon

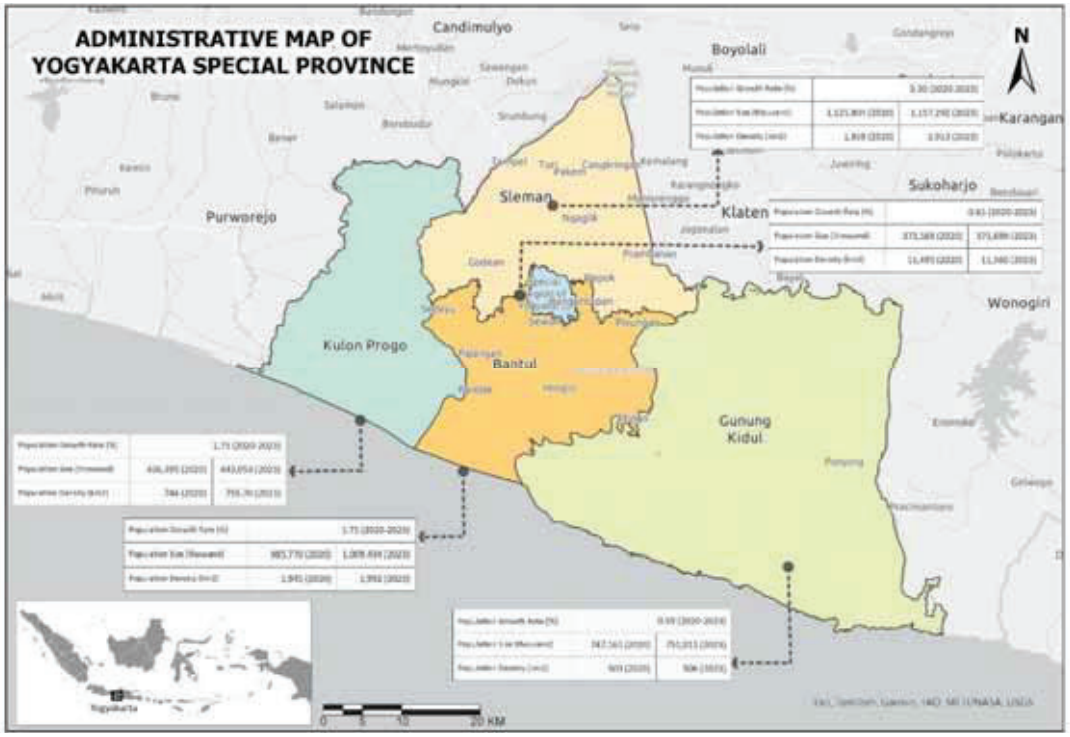

Fig. 1: Geographical location of the study area in the Province of Yogyakarta, Indonesia

emissions in Yogyakarta Province from 2000 to 2023 by decomposing the determining factors and analyzing the amounts of their contributions. To accomplish this, the current study utilizes the LMDI method, which effectively breaks down the intricate factors contributing to carbon emissions and their impacts. The study was conducted in the Province of Yogyakarta, Indonesia, from 2024 to 2025.

MATERIALS AND METHODS

Study area

The study area is situated in the Province of Yogyakarta, Indonesia (Fig. 1). The total area is approximately 3,185.80 square kilometers (km²), which accounts for nearly 0.17% of the country. Its territory is bordered by Central Java province to the north and the Indian Ocean to the south.

The province comprises four regions—Sleman, Kulon Progo, Bantul, and Gunung Kidul—along with a municipality. Among these regions, Sleman has the highest population growth rate (Fig. 1). This trend is associated with the abundance of educational facilities that persistently attracting migrants from surrounding areas. Sleman's population reached nearly 4.06 million in 2024, representing approximately 31% of the province's total population (Table 1). It is projected that the population will increase to 4.1 million by 2050 (BPS DIY, 2023a).

The development of Yogyakarta is mainly driven by tourism, education, creative industries, and agriculture (BPS DIY, 2024a). Yogyakarta, being the second-largest tourist destination, is undergoing rapid population growth along with extensive physical development. For instance, the construction of a ring road in the 1980s aimed to alleviate traffic congestion in the inner city. Nonetheless, this caused rampant land conversion, highlighted by the alteration of a large portion of once green land into built-up-areas. Consequently, within a matter of decades, the compact urban structure of Yogyakarta developed into a more extensive and fragmented arrangement (Rahajeng *et al.*, 2023a, 2023b). Population growth, however, has also positively impacted the province's Gross Domestic Product (GDP), reaching a rate of 6.14% in 2021 (BPS DIY, 2024b). Key sectors contributing to this were

Table 1: Yogyakarta's statistical agglomeration profile in 2025 (Central Bureau of Statistics, 2025)

Category	Yogyakarta	Indonesia
Area (km^2)	3,170.65	1,892,410.09
Population (million)	4.06	284,83
Population growth rate (%)	0.64	1.09
Population density (people/km^2)	1,193	150
Urbanization (%)	78	60

Table 2: The emission factor of energy sources

Energy	Emission factor	Energy	Emission factor
Urea*	0.20	Industrial Gasoline*	69,300 g/GJ
Gasoline*	69,300 g/GJ	Diesel Oil*	74,100 g/GJ
Gasoil*	74,100 g/GJ	Kerosene*	71,900 g/GJ
Electricity**	0.823 tonCO2/MWh	Coal*	97,500 g/GJ
Industrial lubricants*	0.20	LPG*	63,100 g/GJ

*(IPCC, 2006); **Yogyakarta's Living Environment and Forestry Agency (UGM, 2017).

industry (12.48%), agriculture and forestry (11.50%), information and telecommunication (10.58%), and construction (9.69%). It is important to highlight that each sector, which signifies a distinct category of socio-economic activity, is closely linked to a specific type of land use. Depending on the energy consumed by the activity, each sector will emit a certain amount of carbon, represented by an emission factor (Table 2). Population growth, consequently, is significantly associated with heightened energy usage, which compels the government to bring in energy sources to fulfill local demand (ICLEI, 2013).

Carbon emissions data

Numerous studies have underscored the significant effects of land use on carbon emissions. For example, Xia *et al.* (2019) examined carbon emissions related to land use in 13 cities of the 201 Yangtze River Delta region from 1995 to 2015, concluding that industry and transportation were the

202 main contributors (Xia *et al.,* 2019). To determine carbon emissions, information regarding energy usage and land utilization is necessary. In this study, the data are specified in Table 3, with sources primarily from governmental agencies, such as Yogyakarta's Agriculture Agency.

Socio-economic data

Socio-economic activity data from 2000 to 2023 were obtained from the Yogyakarta Province's Central Bureau of Statistics. The data were crucial for calculating the energy consumption of each activity, which ultimately contributes to GHG emissions. Those socio-economic activities are associated with economic sectors (such as agriculture, industry) and land uses. Additional information necessary for the calculation comprised the carbon emission coefficients associated with various energy sources, the economic coefficient for primary crops, and the carbon absorption ratios, all of which were detailed in the IPCC's Guidelines for National Greenhouse Gas Emissions (IPCC, 2006).

Emission factor data

Zhao *et al.* (2021) categorized factor emissions into three key areas: 1) Economic activity, which encompasses agriculture, industry, services, construction, trade, finance, and transportation, 2) Energy intensity, referring to the amount of energy consumed per unit of the region's GDP; and 3) Population growth. Assessing CO_2 emissions involves the use of numerical data from these sectors, with sources presented in Table 3. To address the limitations in emission factor data, this study utilized the formulas published by the Province's Living Environment and Forestry Agency (KLHK, 2017) and the IPCC (2006).

Analysis

GHG emissions generally consist of five components: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and water vapor

Table 3. Types of data and sources of the study.

No.	Data	Specific data	Data source
1	Agriculture	Cultivated lands	Yogyakarta's Agriculture Agency
2	Transportation	Fuel consumption	Yogyakarta's Public Works, Housing, Energy, and Human Resource Agency
3	Industry	Energy consumption	Yogyakarta's Central Bureau of Statistics
4	Households, businesses, and general use	Electricity consumption	Yogyakarta's Central Bureau of Statistics
5	Emission Factors	Coefficients of emission factors	IPCC; Yogyakarta's Living Environment and Forestry Agency
6	Socio-economic activities	Gross Domestic Product	Yogyakarta's Central Bureau of Statistics
7	Population	Population size	Yogyakarta's Central Bureau of Statistics
8	Spatial Planning	Land use maps	Yogyakarta's Regional Development Planning Board Yogyakarta's Land and Spatial Management Agency

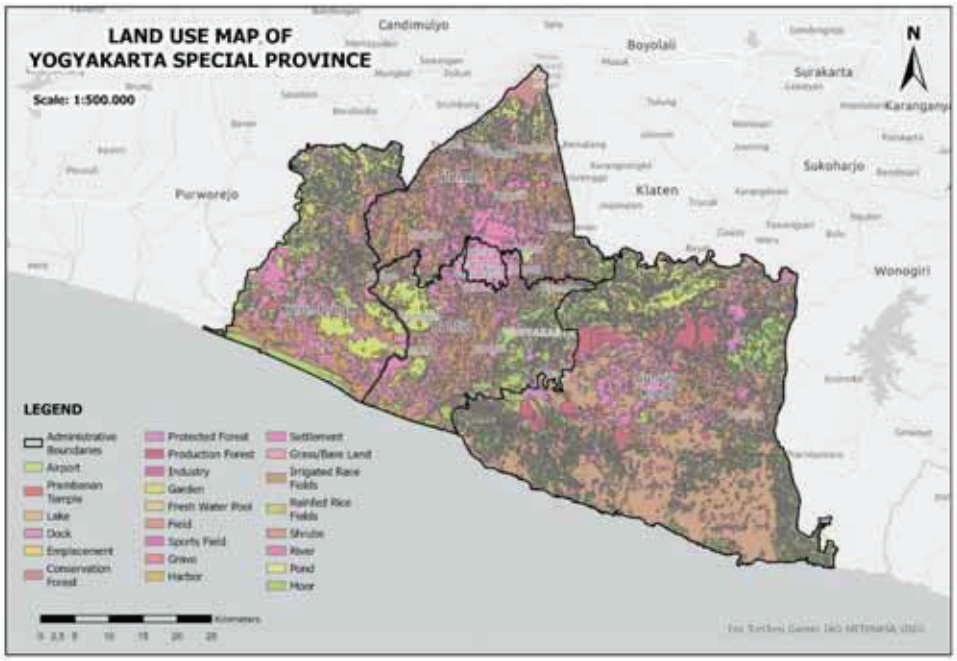

Fig. 2: land use map in the Yogyakarta Province, Indonesia in 2022

(H_2O). Carbon dioxide is produced from burning fossil fuels and deforestation. Methane emissions originate from natural resource extraction, coal mining, and agriculture. Nitrous oxide is generated through the use of synthetic fertilizers and industrial processes. Ozone is linked to human activities that release harmful gases into the atmosphere, which then react to the sunlight. Water vapor results from human activities that boost and amplify evaporation, playing a role in the escalation of global temperature. To estimate CO_2 emissions and assess the effects of land use, the study developed a research framework that centers on LMDI and its five determining factors: land use change, economic development, energy structure, energy intensity, and population growth (Fig. 3). The evaluation of carbon emissions

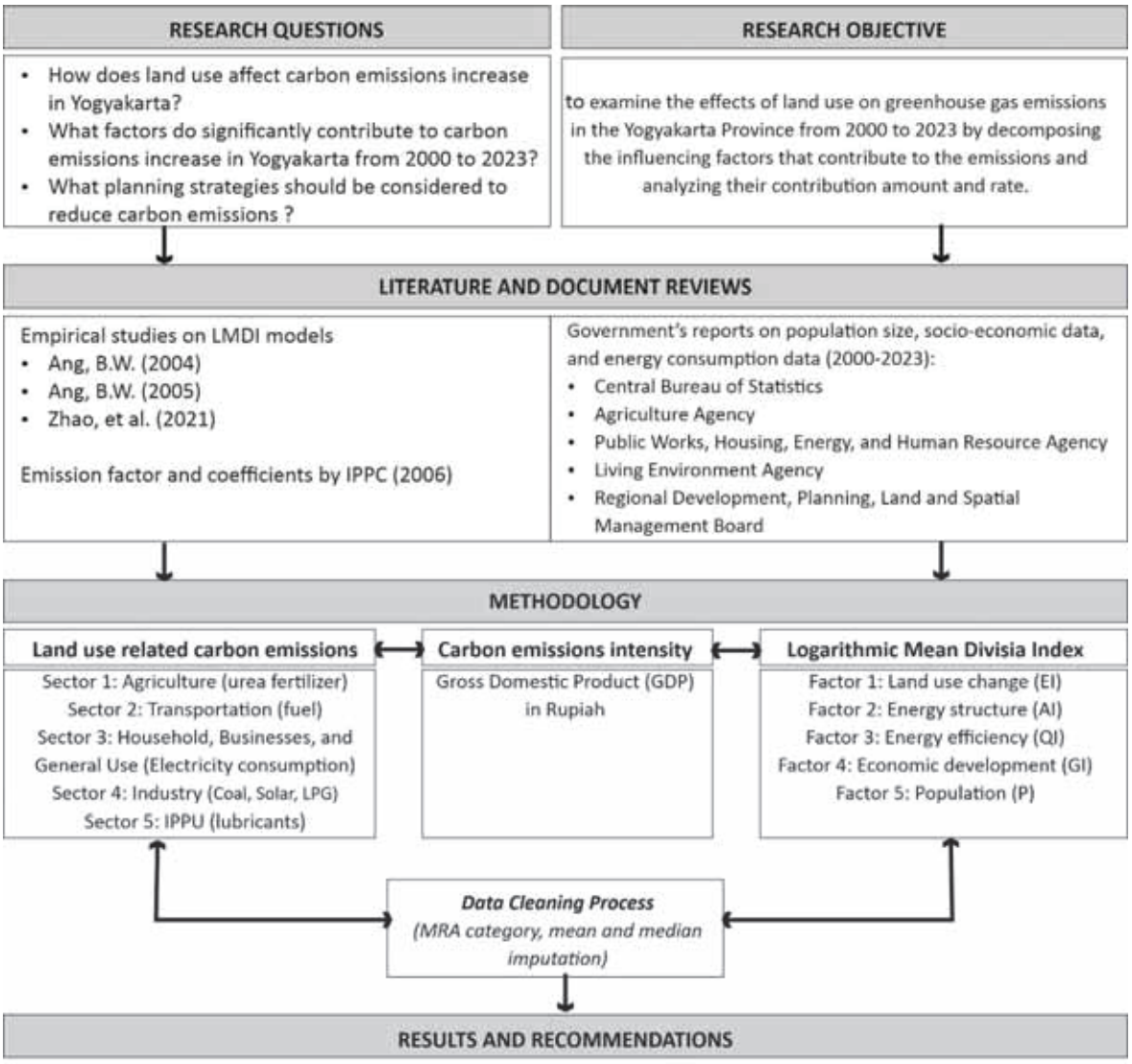

Fig. 3: The study flow diagram

involves the emission factor (EF), a coefficient that signifies the volume of gas emitted for each unit of activity, generally articulated as a measure of energy consumption or production. The coefficient follows the EF guidelines established by the IPCC in 2006, methodologically classified as Tier 1. This category was identified owing to the absence of specific data at the provincial level and the lack of emission factors provided by the national government during the time this study was conducted. Unlike Tier 2 and Tier 3, which involve complex types of modes and activities, Tier 1 offers a simpler methodology based solely on activity data and the EF stipulated by the IPCC. For instance, carbon emission data regarding transportation only concern the aggregates of solar consumption and total fuel purchases at gas stations, without considering the different types of vehicles (KLHK, 2017).

Land use-related carbon emission

The types of land use are categorized as residential, service, commercial, industrial, agricultural, non-agricultural, and others. Carbon emissions related to land use refer to the CO_2 released into the atmosphere

as a result of changes in land use and management.

1. Agriculture

CO_2 can be produced in the agriculture sector through the use of fertilizers containing urea. When the substance is introduced into the soil, it reacts and releases CO_2 into the atmosphere (De Klein *et al.,* 2006). To calculate the emission, this study used Eq. 1 (IPCC, 2006):

$$CO_2E = Murea \times EFurea \quad (1)$$

Where;

CO_2E reflects the total carbon emissions (tons/year), *Murea* represents the agricultural fertilization (tons/year), and *EFurea* represents the urea emission factor (kg/ha).

Eq. 2 (KLH, 2012) is used to calculate the amount of CO_2 emission from the use of agricultural fertilizer per year, where the planted area is the area cultivated by agricultural plants (ha), and the dosage refers to the recommended amount of fertilizer per ha of land (dosage in kg/ha).

$$Murea = Planted\ area\ x\ dosage \quad (2)$$

2. Transportation

Based on the measurement guidelines of the greenhouse inventory, estimating CO_2 emissions for transportation (CO_2E) must follow Tier 1, which considers fuel consumption (FC) and emission factors (EF). The total CO_2 emission (ton C/year) is calculated by multiplying the amount of fuel consumption (liters) by the emission factors (kg CO_2/Tj), depending on the type of fuel, using Eq. 3 (IPCC, 2006):

$$CO_2E = i(FC \times EF) \quad (3)$$

3. Industry

CO_2 emissions pertaining to the industrial sector are calculated using information on the annual fuel consumption of medium and large industries, in conjunction with established emission factors. Nevertheless, the information regarding fuel consumption in the province is restricted limited to lubricants. Eq. 4 (UGM, 2017) is employed to calculate this type of emission (CO_2E in tons C/year). It considers the fuel sold (NEU in liters), the CO_2 emission factor per each fuel type (ODU in kg gas/Tj), the carbon content (CC in ton C/Tj), and the mass ratio of 44/12 representing the ratio of CO_2 to carbon (CO_2/C).

$$CO_2E = i(NEU\ x\ CC\ x\ ODU)a \times 44/12 \quad (4)$$

4. Households, businesses, and general use, and industrial processes and product use (IPPU)

Both sectors, which encompass households, businesses, and general uses, in addition to IPPU, are key contributors to CO_2 emissions, primarily driven by electricity usage. Eq. 5 (UGM, 2017) is used to calculate the total emission from the energy consumption (CO_2E in j) in each of those sectors, where Qi represents the amount of energy consumption (j), CFi represents the carbon emission coefficient (j), Y refers to the population, and λ denotes the carbon emission coefficient per capita.

$$CO_2 2E = jj\ \ QiCFi + Y\lambda \quad (5)$$

In this study, the calculation of CO_2 emissions followed the Tier 1 set by the IPCC (2006). The carbon emission coefficients were published in the government's Inventory and Performance Guidelines of Greenhouse Gas Emissions of Yogyakarta (UGM, 2017).

Carbon emission intensity (CI)

The term carbon intensity indicates the level of carbon dioxide emissions associated with each unit of GDP. Estimating CI helps measure and evaluate the economic efficiency gained from implementing a low-carbon economy. CI is calculated by dividing the GDP by the total carbon emission (CE), using Eq. 6 (Zhao *et al*., 2021):

$$CI = GDP/CE \quad (6)$$

This study adopted a data-cleaning process to address missing, inconsistent, and incomplete data variables. The process is vital for elevating data quality prior to analysis. It commenced with the detection of anomalies, followed by error diagnosis and the application of relevant corrective actions (Austin *et al.,* 2021). Determining an appropriate corrective measure can only be done after the underlying causes of the missing data are known. In this study, the lack of data stemmed from the source's inadequate information, which caused them to be classified as missing completely at random (MCAR) (Roberts *et al*., 2018; Alwateer *et al.,* 2024). The

study subsequently opted for the single imputation approach, which substitutes the missing value with a particular value (i.e., the mean or median of the existing values), as the corrective strategy (Dettori *et al.,* 2018). Finally, the specific imputation method was determined by evaluating whether the mean and median of the non-missing datasets are almost equal and the data distribution is statistically normal. When these conditions are fulfilled, mean imputation is implemented. In contrast, if they are not fulfilled, median imputation is applied to fill in the missing values.

Handling missing data

Conducting emission studies at the local level, particularly in developing countries, can be challenging due to concerns about data availability. Most emission studies, especially those in SEA, were performed at scales broader than a region or a province. Typically, data related to research (including land-use and carbon emissions) at this spatial scale was readily obtainable, with the World Bank being the primary source. In this section, methods for addressing missing data, commonly encountered in studies with cases at the local or regional level, are discussed. With respect to the missing emission-related data, the ongoing study performed a data-cleaning procedure. If not handled properly, missing data can compromise the research's credibility, leading to incorrect inferences, weak statistical power, and a generalizability problem (Alwateer *et al.,* 2024). It is vital to evaluate and diagnose the fundamental reasons for the missing data before taking any corrective measures (Austin *et al.,* 2021). In this study, the missingness is attributed to the source's lack of data, resulting in it being categorized as MCAR (Roberts *et al*., 2018; Alwateer *et al.,* 2024). Based on this, the study then employed the single imputation method. Technically, it replaces the missing value with a specific value (i.e., the mean or median of the non-missing values) (Dettori *et al.,* 2018; Alwateer *et al.,* 2024; Abazz, 2025). The remedial measures were then re-evaluated through a statistical test. If the mean and median of the datasets without missing values are statistically equivalent and the data follows a normal distribution, mean imputation is utilized. Conversely, if those conditions are not met, median imputation is used. In the present study, mean imputation was applied to the agriculture and transportation datasets, while median imputation was applied to the industry and IPPU datasets. Regarding the land use data, satellite remote sensing is considered a promising tool (Agustiyara *et al*., 2025; Ye and Ming, 2023) given its ability to capture extensive land coverage at high speed. It can assist in observing environmental shifts on a broad scale to create carbon emission data, including Nighttime Lighting (NTL) data and carbon satellite data that are linked to human activities (Wang *et al.,* 2025). For instance, Oda *et al.* (2019) utilized NTL to develop a 1-km resolution longitudinal inventory of global carbon emissions from energy sources. Not only is remote sensing beneficial for collecting data, but it also aids in better interpreting the influence of land use on carbon emissions through the analysis of spatial autocorrelation. As an illustration, remote sensing can aid assist in the estimation of carbon emissions via spatial visualization models (Huang *et al*., 2025) and can also detect CO_2 accumulations, effectively identifying hotspots in the 50 Belt and Road countries (Li *et al*., 2025).

Logarithmic mean divisia index

LMDI is a decomposition method largely used to analyze and identify the specific factors that drive changes in carbon emissions. The method's effectiveness and its success in passing the factor-reversal test without any unexplained residuals have significantly contributed to its extensive use. The results can provide a critical foundation for recommending a set of land-use-related policies or planning interventions aimed at reducing GHG emissions (Ang, 2005; Wang, 2024; Zhao *et al.,* 2021). The LMDI technique was first proposed by Ang (2005) to assess shifts in industrial energy consumption by taking into account three factors: the activity effect, the structure effect, and the intensity effect (Ang, 2005). This method analyzes energy changes by breaking down data into various components (Ang, 2005). Zhao *et al.* (2021) categorized the decomposed factors into land use change (EI), energy structure (AI), energy efficiency (QI), economic development (GI), and population (P), using Eq. 7 (Zhao *et al.,* 2021).

$$EI = \frac{E}{A};\ AI = \frac{A}{Q};\ QI = \frac{Q}{GDP};\ GI = \frac{GDP}{P} \quad (7)$$

In order to calculate the total carbon emission (E), Eq. 8 (Ang, 2005) that considers four variables:

land use area (A), energy consumption (Q), Gross Domestic Product (GDP), and population (P) is used:

$$E = \frac{E}{A} \times \frac{A}{Q} \times \frac{Q}{GDP} \times P \quad (8)$$

To estimate the contribution of each factor to the total emission (ΔEI, ΔAI, ΔQI, ΔGI, ΔP), Eq. 9 (Ang, 2005) is utilized by taking into account the outcome of the formula (8), where the Decomposition Residual (ΔErsd) must be 0.

$$\Delta EI = \sum \frac{E^t - E^0}{\ln E^t - \ln E^0} \ln \frac{EI^t}{EI^0} \quad (9)$$

$$\Delta AI = \sum \frac{E^t - E^0}{\ln E^t - \ln E^0} \ln \frac{AI^t}{AI^0}$$

$$\Delta QI = \sum \frac{E^t - E^0}{\ln E^t - \ln E^0} \ln \frac{QI^t}{QI^0}$$

$$\Delta GI = \sum \frac{E^t - E^0}{\ln E^t - \ln E^0} \ln \frac{GI^t}{GI^0}$$

$$\Delta P = \sum \frac{E^t - E^0}{\ln E^t - \ln E^0} \ln \frac{P^t}{P^0}$$

$$\Delta Ersd = 0$$

Finally, the total change in carbon emissions from the base year (E0) to a given year (Et) is calculated by utilizing the decomposition Eq. 10 (Ang, 2005).

$$\Delta Ctot = Et - E0 = \Delta EI + \Delta AI + \Delta QI + \Delta GI + \Delta P + \Delta Ersd \quad (10)$$

RESULTS AND DISCUSSION

Based on the calculations, the relative contributions of five sectors—agriculture, transportation, households, business, and general use, industry, and IPPU—to carbon emissions in Yogyakarta from 2000 to 2023 were obtained and provided in Table 4.

Land-use-related carbon emissions over the period of 2000-2023

As Table 4 indicates, the missing values are distributed randomly throughout the sectors of concern. More than 40% of the total was attributed to the missing values, which were predominantly located in the transportation sector, while the lesser percentages were shared among the agricultural, industrial, and IPPU sectors. The specific imputation method was determined by whether the mean and

Table 4: The land-use-related carbon emission relating to all sectors in 2000-2023 in Yogyakarta (10^3 tC)

Year	Agriculture (Urea fertilizers)	Energy			IPPU (Lubricants)	Overall CO_2 emissions
		Transportation (Fuel)	Households, businesses, and general use (Electricity)	Industry (Gas, coal, solar, kerosene, LPG)		
2023	10,537.50	2,014.68	2,933,363.74	15,294,172.82	373,636.32	18,613,725
2022	12,213.46	1,941.55	2,737,797.66	3,917,338.99	60,282.10	6,729,574
2021	12,197.06	1,328.53	2,558,204.97	15,294,172.82	373,636.32	18,239,540
2020	13,349.39	1,589.68	2,493,049.25	15,294,172.82	373,636.32	18,175,797
2019	12,106.13	1,478.21	2,498,755.52	15,294,172.82	373,636.32	18,180,149
2018	12,270.05	1,478.21	2,351,352.53	15,294,172.82	373,636.32	18,032,910
2017	12,972.41	1,460.27	2,242,248.22	15,294,172.82	373,636.32	17,924,490
2016	14,064.70	1,406.83	2,220,650.55	15,294,172.82	373,636.32	17,903,931
2015	13,473.76	1,328.84	2,044,458.23	87,604,049.99	1,568,603.42	91,231,914
2014	14,031.72	1,283.27	1,950,191.26	30,073,524.86	373,636.32	32,412,667
2013	14,140.76	1,254.65	1,684,039.21	102,770,991.52	7,661,738.63	112,132,165
2012	13,268.77	1,173.82	1,682,007.91	293,227,452.41	4,797,847.17	299,721,750
2011	14,134.99	1,478.21	1,538,819.53	495,936,665.16	5,888,559.38	503,379,657
2010	15,263.95	1,478.21	1,403,989.79	41,895,008.95	3,982,759.18	47,298,500
2009	13,749.64	1,478.21	1,299,066.83	22,437,800.00	2,554,681.20	26,306,776
2008	13,184.95	1,478.21	1,219,336.67	22,763,488.74	181,058.51	24,178,547
2007	13,184.95	1,478.21	1,115,647.87	15,294,172.82	173,494.23	16,597,978
2006	13,184.95	1,478.21	1,105,552.13	5,614,028.16	160,401.35	6,894,645
2005	13,184.95	1,478.21	1,024,149.05	1,719,027.59	184,584.67	2,942,424
2004	13,184.95	1,478.21	930,671.32	3,372,389.78	895,280.35	5,213,005
2003	13,184.95	1,478.21	930,671.32	1,924,324.48	487,473.45	3,357,132
2002	13,184.95	1,478.21	904,155.26	89,639.96	184,099.85	1,192,558
2001	13,184.95	1,478.21	795,437.15	5,876,013.31	173,847.18	6,859,961

median of the non-missing datasets are statistically almost equal, and the data distribution is normal. The datasets in the agricultural and transportation sectors fulfilled these criteria, which resulting in the choice to employ mean imputation for substituting the missing values. The missing values in industry and IPPU, which had non-normal dataset distributions, were addressed using median imputation. In 2023, the total carbon emissions related to land use reached 18,613.725 x 10^3 tons of carbon emissions (tC), which is three times greater than the amount in 2001. However, from 2010 to 2013, there was a notable amount of total emissions. For instance, in 2011, total carbon emissions amounted to approximately 503,379.657 x 10^3 tC. In general, the annual influence of three sectors—agriculture, transportation, and households, businesses, and general use—on carbon emissions remained consistently low and stable. The missing values in the agriculture and transportation sectors helps to clarify why their impacts remain relatively consistent during specific years. According to the government's statistics bureau, urea fertilizer consumption and fuel purchases, which are used to calculate the effects of the two sectors on carbon emissions, reportedly did not experience a significant change over the study period. Additionally, it should be emphasized that merely 20% of local farmers in the province apply urea to enhance their farmland, whereas most relies on organic fertilizers or compost (BPS DIY, 2024d). Regarding transportation, the social distancing mandate during the pandemic seemed to have led to a decline in the effects of those sectors on emissions from 2020 to 2021. Conversely, the roles of the industry and IPPU sectors to the total carbon emissions were marked by instability and significance, especially during the years 2010 to 2013. Additionally, industry, alongside households, businesses, and general use, played a key role in influencing total carbon emissions over the years. However, during 2009-2013, 2015, and 2022, the effects of the IPPU sector outpaced those of the households, businesses, and general use sector, resulting in considerable changes in total carbon emissions (Table 4). The study calculated emissions from IPPU by assessing the lubricant usage in moderate-scale and large-scale industries. The escalation in lubricant consumption is significantly associated with the increasing count of industries registered in those years. Their specific activities cover furniture production, clothing, and food (BPS DIY, 2024b). To conclude, the LMDI findings demonstrate the substantial influence of the three sectors—industry, households, businesses, and general use, along with IPPU—on the total carbon emissions within the province.

A significant aspect to consider is the global pandemic, which, despite its favorable impacts on environmental quality (Ayuningsih *et al*., 2024), led to a drastic decline in economic activities on a global scale (Gagnon *et al.,* 2023). In developing countries like Indonesia, the adverse impacts of COVID-19 continued into 2022. Consequently, Yogyakarta, which relied on tourism and industries for its revenue, faced severe economic setbacks after the pandemic. This highlights the reason for the marked reduction in the total impact of the industry and IPPU sectors on carbon emissions in 2022 (Table 4).

Carbon intensity

Carbon emission intensity refers to the amount of carbon emissions (CE) produced per unit of GDP, presented in USD. CI represents a standard for measuring the carbon dioxide and other GHG emissions associated with a unit of economic activity, highlighting the energy consumption levels in a specific area. The formula for calculating CI is GDP divided by CE. The lower the CI, the more environmentally efficient the process of an activity, which tends to result in a better environment.

As Fig. 4 indicates, the CI trend from 2000 to 2021 was relatively stable. However, over the last three years (2021-2023), the CI experienced significant changes, increasing from 0.36 USD per ton of carbon (USD/tC) in 2021 to 1.03 USD/tC in 2022, before declining to around 1.03 USD/tC in 2023. The tourism industry is the most affected by COVID-19, which makes up about 50% of Yogyakarta's GDP. To address this, the government enacted an emergency regulation, Government Law No. 1 of 2020, which mandated social distancing at the community level, resulting in the temporary closure of public facilities and transportation. In April 2020, the government the government initiated the first state of emergency, imposing restrictions on public movement to and from regions beyond Yogyakarta. Consequently, the number of tourists occupying local hotels declined from 9 million in 2019 to 3.2 million in 2020 (Wahyuni, 2021). During the recovery phase in 2020-2021, the government launched strategies to attract tourists, including the introduction of electronic

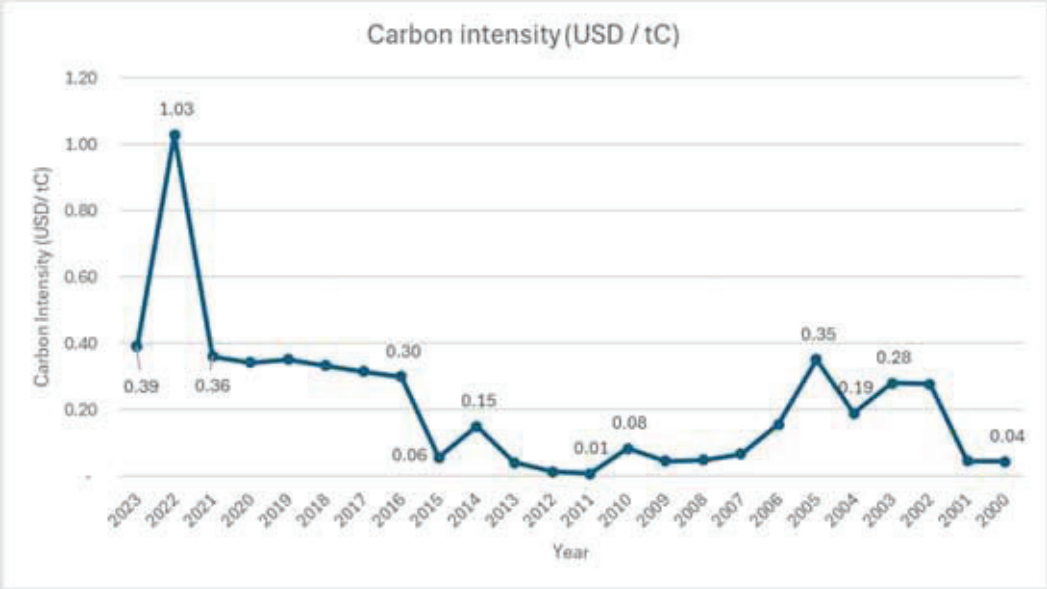

Fig. 4: The amount of carbon intensity by year in the Yogyakarta Province

payments, tourism promotion through the Visiting Yogya application, and self-screening and emergency applications, Jogja Pass. These initiatives successfully enhanced public confidence in local capabilities to manage risks, leading to a rise in visitor numbers and regional GDP. The sharp increase in 2022 can therefore be partly attributed to the ongoing rebound in economic activity, specifically tourism. In 2023, emissions saw a downward trend, which was partly due to a 10% decrease in the number of visitors, particularly international tourists (BPS DIY, 2023c), along with the negative growth experienced in the manufacturing industry (BPS DIY, 2023b).

Decomposing the determining factors of land-use-related carbon emissions

From 2000 to 2023, the changes in total CO_2 emissions (Table 5) were subsequently analyzed by decomposing them into the identified factors through the application of the LMDI. The objective of this approach is to examine the effects of each factor —namely, land use change (ΔEI), energy structure (ΔAI), energy efficiency (ΔQI), economic development (ΔGI), and population (ΔP) — on total carbon emissions. LMDI serves as a useful tool for assessing how various elements influence total carbon emissions, the variations in emissions from one year to the next, and determining which factors have the greatest contribution to carbon emissions in the province. Table 5 shows the annual contribution of each factor to carbon emissions. A positive contribution value indicates that a factor leads to an increase in emissions. A lower value indicates a stronger reduction in CO_2 emissions by the factor; in contrast, a higher value signifies an increase in emissions due to the factor.

To compare the contribution of each determining factor to the overall amount of carbon emissions, the proportion was calculated and expressed as a percentage (Fig. 5). Typically, changes in land use represent the largest factor, contributing to 47% of overall emissions. Following it, the economic development contributes 31%, while the energy structure accounts for 19% of the total emissions. During the course of the study periods, it is evident that these three factors have substantially contributed to the variations in carbon emissions.

The significant contribution of land use change to carbon emissions (47%) is particularly evident from the factor's effects in 2010-2011 (98.68×10^3 tC), 2022-2023 (25.65×10^3 tC), and 2002-2003 (22.36×10^3 tC) (Fig. 6). During the 2010-2011 period, other factors-energy structure (9.27×10^3 tC), economic development (7.10×10^3 tC), and population (2.40×10^3 tC)-also contributed to the increased land-use-related carbon emissions. The agricultural land is the specific type of land use that has undergone changes during the study period.

Table 5: The contribution value of each factor by year based on the LMDI calculation (10^3 tC)

Year	ΔEI	ΔAI	ΔQI	ΔGI	ΔP	ΔC
2023-2022	25.65	8.95	-0.01	7.31	-0.1	41.8
2022-2021	-0.85	-2.01	7.67	7.15	-1.01	10.95
2021-2020	6.93	7.86	-0.16	7.2	0	21.83
2020-2019	6.91	7.4	-0.02	7.51	0	21.8
2019-2018	6.97	6.91	-0.04	7.2	0.01	21.05
2018-2017	6.95	8.21	-0.25	7.22	0.01	22.14
2017-2016	6.91	6.41	7.19	7.14	0	27.65
2016-2015	-0.04	-0.21	7.04	7.12	-1.65	12.26
2015-2014	22.35	7.61	-0.02	7.11	1.05	38.1
2014-2013	-0.35	-1.2	-0.03	7.13	-1.26	4.29
2013-2012	-0.34	-0.92	-0.03	7.15	-0.99	4.87
2012-2011	-0.3	-0.51	-0.03	7.13	-0.52	5.77
2011-2010	98.68	9.27	-0.03	7.1	2.4	117.42
2010-2009	13.47	7.49	-0.37	26.11	0.58	47.28
2009-2008	7.61	6.99	-0.02	7.09	0.39	22.06
2008-2007	10.61	7.28	-0.05	7.33	0.08	25.25
2007-2006	18.74	7.79	-0.02	7.08	0.89	34.48
2006-2005	18.18	7.76	-0.01	6.96	0.86	33.75
2005-2004	-0.29	-0.51	-0.03	7.07	-0.58	5.66
2004-2003	11.41	7.35	-0.01	6.92	0.45	26.12
2003-2002	22.36	7.94	-0.36	22.09	1.05	53.08
2002-2001	-0.28	-1.61	-0.04	7.14	-1.78	3.43
2001-2000	6.91	6.91	-0.01	-0.01	0	13.8
2000-2023	288.19	115.16	20.36	191.25	-0.12	614.84

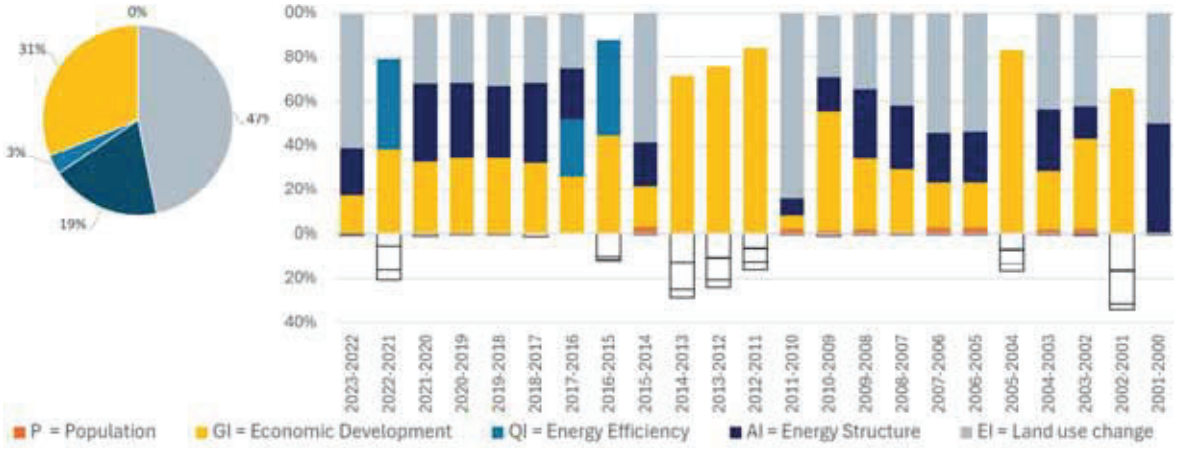

Fig. 5: The cumulative emission contribution rate (a) and the annual contribution rate (b) of each factor to Yogyakarta's carbon emissions from 2000 to 2023

Its total area saw a significant decrease from 167.26 ha in 2001 to only 96.28 ha in 2022. In contrast, that of other land uses (e.g., residential, commercial, and public services) increased over time (BPS DIY, 2011). These outcomes can be associated with the flourishing housing market during that period, which resulted in the significant transformation of agricultural land into urbanized spaces. The phenomenon was particularly pronounced in Sleman, the largest regency, which was the primary rice supplier for the province. According to reports, the province's agricultural areas are diminishing by approximately 250 ha annually due to heightened urban development and infrastructure expansion (Wibawanti *et al.*, 2022). Years prior, the

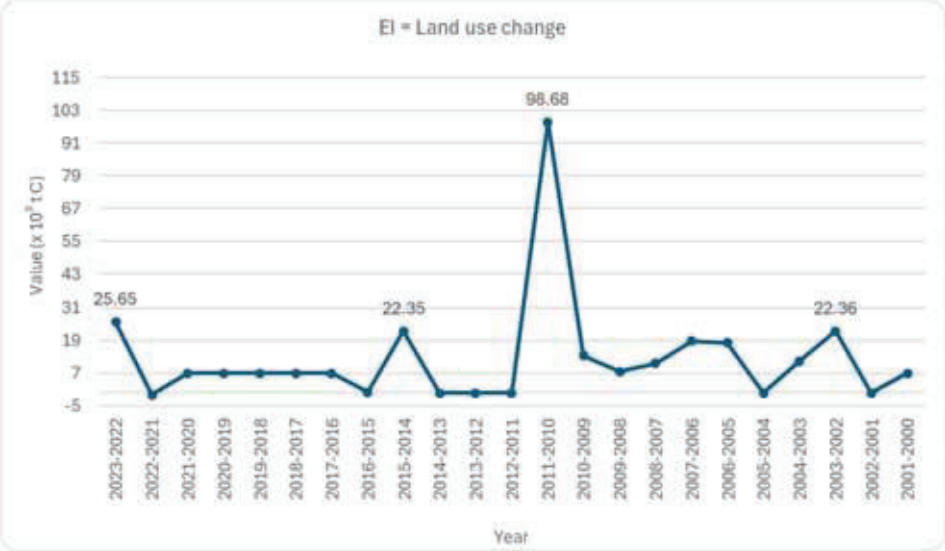

Fig. 6: The contribution value of land use change factor to the carbon emission by year

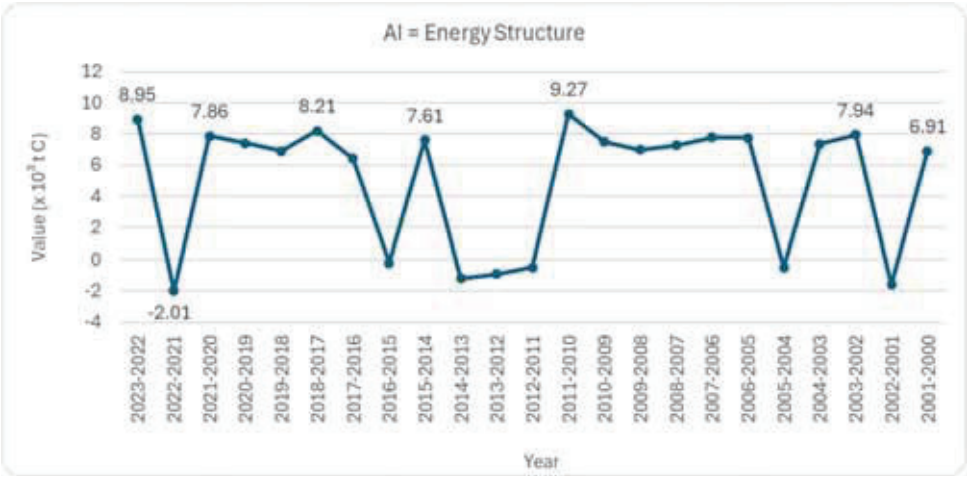

Fig. 7: The contribution value of energy structure factor to the carbon emission by year

provincial government issued Regulation No. 5 of 2007 concerning Green Spaces Management and Regulation No. 6 of 2010 concerning the Provision of Private Green Spaces. Nevertheless, the absence of control over land-use conversion practices, coupled with the government's inconsistency in enforcing regulations, has led the province to face a decline in open spaces (Widowati, 2013). It should be noted that merely 79.87% of the province's overall area has been developed while adhering to the government's land use plans. While 9.64% have not yet complied, and 10.49% did not comply with such plans (KLHK, 2022).

The energy structure encompasses how energy is produced, consumed, distributed, stored, and transformed. Its contributions to carbon emissions relatively inconsistent over the years, ranging from a decrease of 2.01 x 10^3 tC in 2021-2022 to an increase of 9.27 x 10^3 tC in 2010-2011 (Fig. 7). Additionally, the energy structure was responsible for 19% of total carbon emissions, ranking it as the third largest contributing factor.

The energy efficiency factor contributed merely 3% to

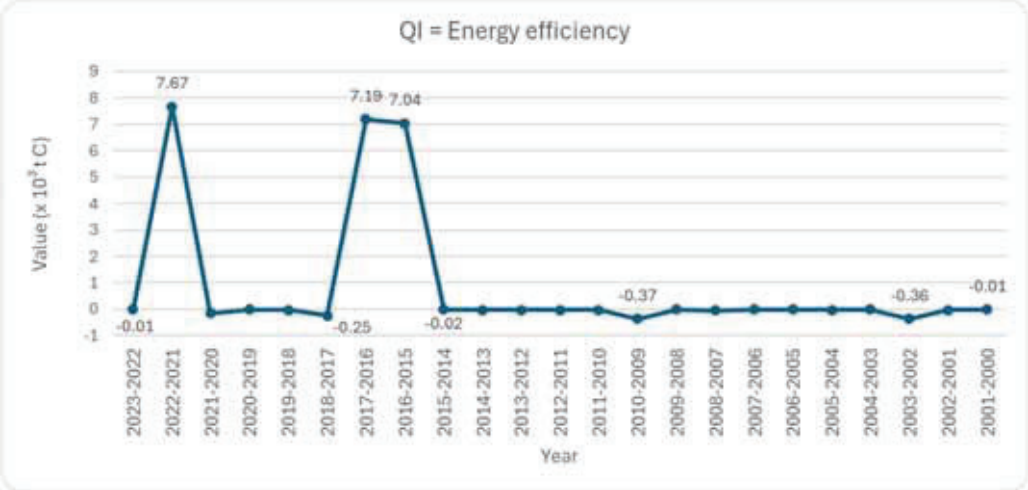

Fig. 8: The contribution value of the energy efficiency factor to the carbon emission by year

the overall impact on carbon emissions in the province. During the periods of 2000-2015 and 2017-2021 (Fig. 8), the factor had an insignificant effect on carbon emissions, indicating its minimal role in the overall change in total carbon emissions. Its contribution to land-use-related emissions was positive only during certain periods, peaking at 7.19 × 10^3 tC between 2015 and 2017 and 7.67 × 10^3 tC between 2021 and 2022. The restrictions associated with the pandemic likely contributed to a more efficient energy consumption pattern, resulting in a significant reduction in usage across different sectors. The insignificant contribution of energy efficiency to carbon emissions could also be attributed to the lack of enforcement of environmental policies and regulations, as well as inadequate control over their implementation. In recent years, the government has initiated multiple programs aimed at reducing emissions, such as implementing carbon taxes on industries that generate fossil fuels and promoting a campaign for non-vehicular mobilization. However, these did not appear to be sufficient for substantially reducing carbon emissions. Energy consumption from fuel, electricity, and gas generated by households, transportation, commercial, and industrial sectors remains high in terms of its effects on carbon emissions (DIY, 2019).

The economic development is the second most significant factor contributing to increased land-use-related carbon emissions, accounting for 31% of the total effects on carbon emissions. The peak of its contribution occurred in 2009-2010, which reached 26.11 x 10^3 tC (Fig. 9). According to the province's Central Bureau of Statistics, the GDP increased by 6.1% in 2010, with the transportation sector being the largest contributor (Central Bureau of Statistics, 2023). The trend in emissions is closely linked to the primary economic driver of the province, tourism, which is reflected in the government's GDP assessment through the count of hotel occupancy rates. Major natural disasters (earthquake and eruption) in 2010 suppressed tourism and its multiplying effects on other sectors (BPS DIY, 2011), causing a decrease in GDP and the economy's impact on emissions in 2011.

Of all the factors, the population has the smallest effect on the total effects on carbon emissions in the province. Its highest contribution to emissions only in certain periods: 1.05 x 10^3 tC in 2002-2003, 2.4 x 10^3 tC in 2010-2011, and 1.05 x 10^3 tC in 2014-2015 (Fig. 10). Overall, there is a direct relationship between population growth and carbon emissions, influenced by various human activities like deforestation, land use change, and traffic congestions. The more the population size, the greater the energy consumption and the emissions will be (Ribeiro *et al.,* 2019). Nonetheless, the study indicates that population growth by itself, assuming steady per capita emissions, may not fully explain the rise in carbon emissions (Cohen, 2010).

Based on an examination of the effects of the determining factors on carbon emissions from 2000

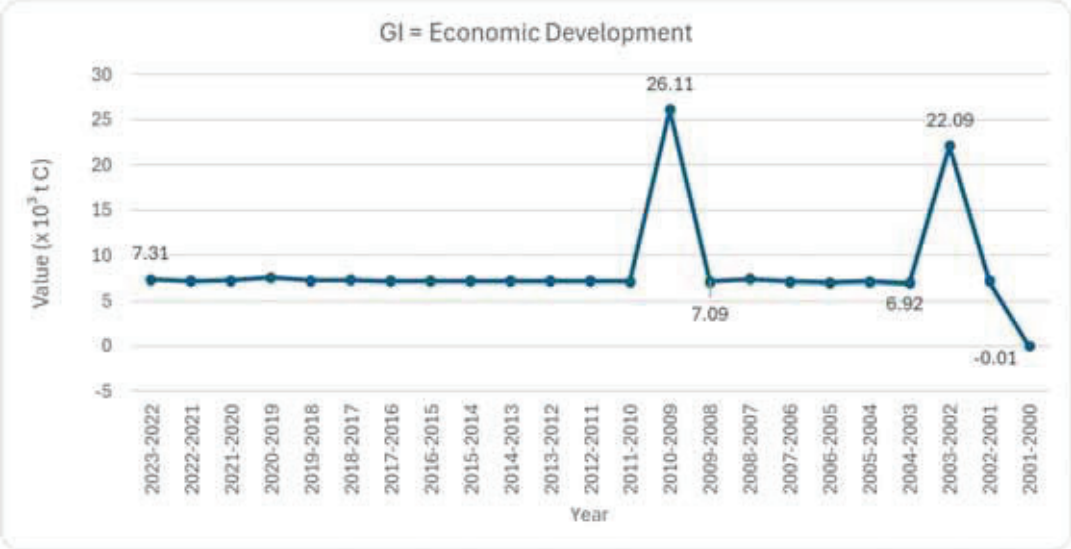

Fig. 9: The contribution value of the economic development factor to the carbon emission by year

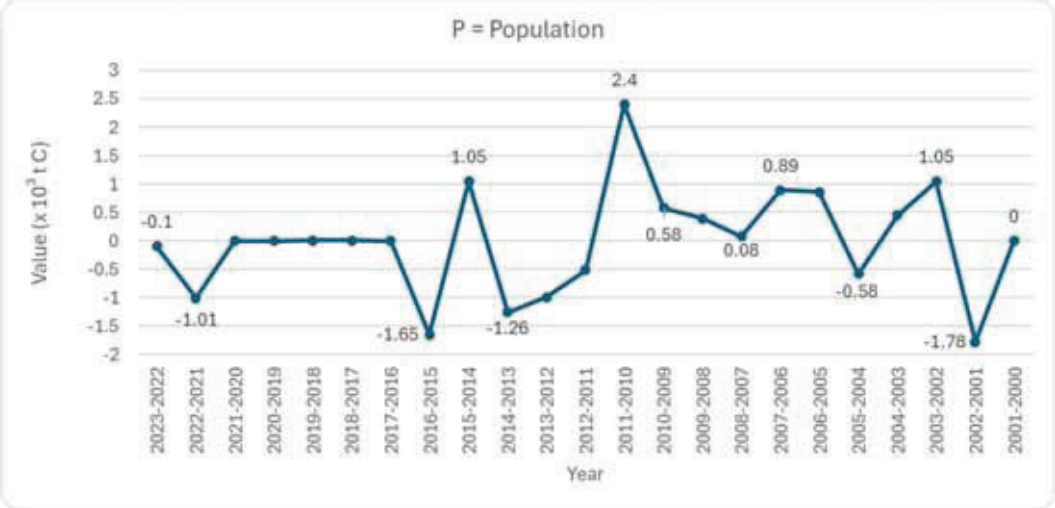

Fig. 10: The contribution value of the population factor to the carbon emission by year

to 2023, it was found that land-use change was the primary driver of increased carbon emissions in Yogyakarta. It contributed 288.19 × 10^3 tC to the increase in carbon emissions, accounting for 47% % of the total emissions. Nonetheless, the impact of this factor varied significantly over time. For instance, its role in carbon emissions began to decline from 2011. During particular times, changes in land use had a negligible influence on carbon emissions relative to prior years. Notably, there was a significant rise in its effects during the period from 2010 to 2011, with an increase of 98.68 × 10^3 tC, leading to a total amount of 117.42 × 10^3 tC. Economic development is the second-largest contributor to land-use-related emissions, accounting for a total of 191.25 × 10^3 tC of emissions increases, which represents 31% of the total effect. Its significant contribution occurred during the years 2009-2010 and 2002-2003, with a relatively stable contribution to emissions over certain periods. Consequently, economic development plays

an essential role in affecting carbon emissions in the province. The third most important factor contributing to emissions is the energy structure, which accounts for 115.16×10^3 tC, or 19% of the total effect on emissions. The influence of this factor has varied throughout the years. For instance, it had a considerable impact on emissions growth during 2022-2023, yet it played a minimal role in emissions increases in the earlier period (2021-2022). This phenomenon can be linked to the ongoing repercussions of the global pandemic, which have led to economic disruption and, consequently, reduced energy consumption across economic sectors. This result is consistent with a different study, which proposed that the pandemic led to a slow uptick in emissions in Indonesia (Sudarmaji *et al.,* 2022). Two other factors, namely energy efficiency and population, made relatively insignificant contributions to emission increases from 2000 to 2023, accounting for 20.36×10^3 tC and 0.12×10^3 tC, respectively. This represents 3% and 0% of the total effect. Both factors exerted less effect on land-use-related emissions, which have shown a declining trend over the years. The energy efficiency factor, however, did help reduce emissions during certain periods. The study indicates that changes in land use are the primary factor influencing emissions related to land use, with economic development being the next most significant factor. The result demonstrates that land use conversion and subsequent losses of agricultural lands have been alarming (Partoyo and Shrestha, 2017). Similarly, Zhao *et al.* (2021) also highlighted land-use change as the primary contributor to emissions increases in the Pearl River Delta from 1990 to 2015, with economic development and population growth following. Furthermore, both studies corroborated the negligible impact of energy efficiency on emissions associated with land use, stressing the importance of advancing energy efficiency initiatives to lower carbon emissions. The other finding—that economic development has a significant impact on emissions in Yogyakarta—reinforces the findings of other studies in the SEA region, which suggest that economic factors are the primary drivers of emissions in the region (Khusna and Kusumawardani, 2021; Kim *et al.,* 2025; Lisaba and Lopez, 2021). Yogyakarta continues facing rapid urbanization due to its status as the nation's second-largest tourist destination and education hub. Throughout the two decades, the province has seen a rise in carbon emissions, which can be primarily linked to three economic sectors: 1) industry, 2) households, businesses, and general use, and 3) IPPU. With respect to the factors that influence carbon emissions, alterations in land use, economic advancement, and energy frameworks have exerted a positive and substantial effect on emissions linked to those sectors and land uses. Promoting energy efficiency in the province's development can contribute to a reduction in GHG emissions, although implementing it is known to be extremely challenging for policymakers in the country (Sudarmaji *et al.,* 2022). In conjunction with improving energy efficiency, additional measures to decrease carbon emissions should encompass bolstering land law enforcement and making sure that land zoning corresponds with local activities to prevent unfavorable land use changes, moving towards renewable energy sources, implementing clean technologies, providing incentives, and enhancing waste management. Yogyakarta currently faces a significant waste problem, generating approximately 2,117 tons of waste per day due to intense tourism and urbanization (Azizah, 2024; Daeng, 2024). The closures of some existing landfills have exacerbated this issue. Ultimately, to decrease carbon emissions, it is essential to foster public awareness via environmental education and campaigns, in addition to implementing effective land zoning policies, land use planning, land use restrictions, and carbon pricing strategies (Wang, 2024). When implementing carbon policies, policymakers should consider both the economic trade-offs (e.g., increased production costs) and social trade-offs (e.g., uneven distribution among local groups).

CONCLUSION

Controlling carbon emissions is a critical aspect of sustainable development, with land use planning playing a significant role in reducing emissions. Nevertheless, investigations that evaluate the influence of different elements and land use on carbon emissions, especially at the community scale, is still scarce. To address this gap, an empirical study was conducted in Yogyakarta, an economically growing and densely populated province in Indonesia. This study identified three sectors: 1) industry, 2) households, businesses, and general use, and 3) IPPU, which have significant effects on carbon emissions, especially in 2009-2013, 2015, and 2022. Other sectors—agriculture and transportation— demonstrated fairly consistent

and negligible effects. Regarding carbon intensity, the results showed consistency from 2000 to 2021. However, there was an exponential increase in 2022, which coincided with the resurgence of economic activities after the global pandemic, followed by a significant decline in 2023. Fundamentally, LMDI has facilitated this study in assessing the impact of different elements on carbon emissions. Land use change was evident as the primary driver, accounting for 47% of the total effect. Following this, the economic development contributed 31%, and the energy structure contributed 19% of the total effects. Two other factors, energy efficiency and population, contributed little and in an inconsistent manner across the observed intervals. Methodologically, LMDI has proven effective in enhancing the current understanding of factors driving land use-related emissions, enabling the identification of their effects on emissions changes. The revelation that land use change are the leading cause of carbon emissions throughout the years underscores the concerning issue of land conversion and the subsequent decline of agricultural areas. Weak land law enforcement, evidenced by less than 80% of lands being developed in compliance, is arguably responsible for this issue. It is essential for policymakers to make sure that land zoning corresponds with local activities to reduce negative changes, emphasize the protection of agricultural lands, and support carbon incentives and costs in their areas. Despite the potential of LMDI, further research is needed, particularly considering the inconsistent and limited factors examined in most studies. Ideally, the greater the number of influencing factors, as long as they are intercorrelated and within the study's interest, the more robust the findings will be. Following the golden rule, other factors (e.g., digital technology) that may have been overlooked should be considered in the future. This study, while important, is not free from limitations. First, emission factors stipulated by the Indonesian government were not available, prompting the study to use Tier 1, a default from the IPCC. Future studies should consider the use of Tier 2 or Tier 3 by ensuring the availability and completeness of the required data, including national-level emission factors. Second, data related to certain sectors in specific periods were unavailable at both the provincial and regional levels. As previously mentioned, absent data can jeopardize the reliability of the information, which may lead to inaccurate conclusions and a diminished ability to generalize the results. The mean and median imputations, as corrective measures, are simple and fast; however, they may result in biased estimates and an underestimation of standard errors, particularly for datasets with missing values exceeding 40%. Future studies should consider employing sophisticated methods, such as multiple imputations, k-nearest neighbors, and deep learning, to improve the accuracy of the results. Third, ArcGIS shapefiles indicating the geographic features of the province's regencies over the years were also unavailable. Consequently, this obstructed the study's capacity to further interpret and visualize the dynamics of urban patterns concerning carbon emission trends. Future studies ought to integrate remote sensing techniques to acquire high-resolution information about regions with a similar spatial dimension. Fourth, since LMDI does not explicitly analyze the interactions between the effects of the involved factors, future studies should also consider combining LMDI with another statistical technique, such as bootstrap decomposition. The integrated methods could even enable researchers to develop scenario-based models to project energy consumption and its subsequent carbon emissions.

AUTHOR CONTRIBUTIONS

C.D.A. Depari, the corresponding author, contributed to supervising the first author in conducting the research, interpreting the data, drawing conclusions, and visualizing the results. S.H.P. Wicaksono collected the research data, analyzed the data, and prepared all tables, maps, graphs, including the manuscript draft under the supervision of C.D.A. Depari.

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CONFLICT OF INTEREST

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

and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
AI	Activity intensity
BPS	Badan pusat statistik
CC	Carbon content
CE	Carbon emission
CH_4	Methane
CI	Carbon intensity
CO	Carbon Monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DIY	Daerah Istimewa Yogyakarta
DOLS	Dynamic ordinary least squares
EF	Emission factor
EI	Emission Intensity
FC	Fuel consumption
GDP	Gross domestic product
GIS	Georaphic information system
GHG	Greenhouse gas gases
GI	Growth index
GTWR	Geographically and temporally weighted regressions
ha	Hectare
H_2O	Water
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial processes and product use
kg	Kilograms
km^2	Square kilometer
LGV	Liquefied gas for vehicles
LMDI	Logarithmic mean divisia index
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MCAR	Missing Completely At Random
N_2O	Nitrous oxide
NEU	Non-energy use
NG	Natural gas
NO	Nitrous oxide
O_3	Ozone
ODU	Oxidation during use
P	Population
Pb	Lead
QI	Quality index
SEA	Southeast Asia

SO_2	Sulfur dioxide
Tj	Terajoule
tC	Tons of carbon emissions (CO_2)
USD	US Dollar

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CASE STUDY

Environmental and financial assessment of phosphorus loss from food waste in the academic institutions

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ABSTRACT

BACKGROUND AND OBJECTIVES: Food waste is a global issue as it has an environmental impact by releasing large amounts of carbon dioxide equivalent throughout their biodegradation. Academic institutions are significant sources of food waste, as students spend over 15 years of their lives living and learning in these environments. Considering the intake of two to three meals daily, a significant quantity of food waste may be produced. Regrettably, a significant amount of food waste usually finds its way to landfills; as a result, the valuable phosphorus it held is lost during disposal. The study objectives were to investigate the practical management of food waste in academic institutions, especially in the part related to phosphorus recovery.

METHODS: Three academic institutions in the Bangkok area were chosen, i.e. a primary school, a technological college, and a public university. For three consecutive weekdays, sampling was performed at each institution. Solid waste generated from the kitchen and canteen in this study was categorized into food waste, general waste, and recyclable waste. Waste weights were recorded and their physical and chemical characteristics were analyzed. The phosphorus mass flow was determined according to mass balance concept.

FINDINGS: The study indicated that the quantity of food waste generated by three institutions varied between 20 and 206 kilograms daily. In comparison to their total solid waste (41–229 kilograms per day), food waste accounted for 40–90 percent of the total waste generated by three academic institutions. This study categorized food waste into two distinct types: uncooked food waste and cooked food waste. The phosphorus content of uncooked food waste ranged from 0.09 to 0.29 milligrams phosphorus per gram, whereas those of cooked food waste ranged from 0.53 to 0.76 milligrams phosphorus per gram. From mass balance calculation, the total phosphorus mass entering the waste management system possibly ranged from 7.9 to 141.3 grams' phosphorus per day, while phosphorus loss ranged from 2.3 to 13.5 grams per day. According to the composting scenario analyzed in this study, the projected yield of fertilizer-like products varied from 0.3 to 19 tons annually. The utilization of food waste could reduce waste collection and disposal costs by up to 1,395–1,870 United States Dollar per year. Furthermore, extracting phosphorus from food waste may contribute to mitigating the challenge posed by restricted global phosphorus reserves.

CONCLUSION: Academic institutions in this study generated substantial amount of food wastes, with notably high levels observed at the primary school implementing a centralized food preparation approach. Analysis of the food waste characteristics showed considerable nitrogen and phosphorus content, indicating its potential for nutrient recovery. Composting this waste could facilitate phosphorus reclamation, offering both environmental and economic benefits. This study firmly suggested for the efficient segregation of food waste to improve the evaluation of phosphorus flow and recovery. It is vital to prioritize phosphorus recovery for agricultural purposes.

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INTRODUCTION

Approximately 1.3 billion tons of food are lost or wasted globally each year, representing nearly one-third of total food production. In Europe and North America, food waste generation is estimated at 95–115 kilograms per capita per year (kg/capita/y), whereas in sub-Saharan Africa and South and Southeast Asia, it amounts to only 6–11 kg/capita/y. Food waste is largely a consumption issue in medium- and high-income countries, but in low-income countries, the losses are primarily seen in the earlier phases of the food supply chain, notably during production and post-harvest handling (Gustavsson *et al.,* 2011). Food waste is responsible for approximately 3.3 gigatons (Gt) of carbon dioxide (CO_2) equivalent in greenhouse gases (GHGs) emissions–or up to 4.4 Gt of CO_2 equivalent when land use change is included–representing about 8 percent (%) of total global emissions, and ranking just behind China and the Unites States. Moreover, food waste results in an estimated annual economic loss of approximately 936 billion United States dollars (USD) annually (FAO, 2013, 2015). According to the United Nations Environment Programme (UNEP, 2021), consumer and retailer food waste accounted for 17% of total food waste, comprising 11% from households, 5% from food service, and 2% from retail sectors. This report estimated that approximately 931 million tons of global food waste were generated in 2019 (UNEP, 2021), with an average of 74 kilograms per capita–a figure consistent across low-, middle-, and high-income countries. In Thailand, according to the Pollution Control Department (PCD, 2022) food waste accounted for 39% of total municipal solid waste in 2021, amounting to approximately 9.7 million tons, or 146 kilograms per capita per year. According to Liu *et al*. (2020), it was estimated that in 2018, the food waste generated in Bangkok was roughly 0.61 kilograms per person per day, equating to a daily total of 5,669 tons. However, in 2020, food waste in Bangkok decreased to approximately 4,323 tons per day, largely due to lockdown measures implemented during the Coronavirus Disease 2019 (COVID-19) pandemic and a significant decline in tourism (DOE, 2021). Furthermore, sanitary landfilling (or in some cases, open dumping) still accounts for approximately 57% of food waste management in Thailand, while the remaining portion is directed to incineration or composting facilities (TDRI, 2019). Consequently, despite the implementation of several measures, food waste management in Thailand still encounters challenges regarding its effectiveness and long-term sustainability. People commence their engagement with educational institutions as early as two or three years of age. Over the course of their compulsory education, which spans the first nine years of primary and secondary schooling, students spend approximately 7,634 hours (or an average of 848 hours per year) in schools and similar institutions (OECD, 2023). Thus, activities associated with food, such as meal prep, food sales, and waste disposal, play a vital role in the routine operations of institutions. In particular, many academic institutions and schools are equipped with on-site dormitories, resulting in sustained food consumption throughout the day. As reported by Wilkie *et al*. (2015), food waste represented about 52.2 grams per student daily, making up a significant portion of total waste, which varied between 47% and 58%, across three schools in Florida. In 2019, food waste from 46 U.S. schools was estimated at 530,000 tons, resulting in approximately 1.9 million metric tons of CO_2 equivalent ($MtCO_2e$) emission and incurring economic losses of 1.7 billion USD (WWF, 2019). At the university level, a study conducted at a Midwest reported that an average of 57 grams of leftovers were discarded per tray (Whitehair, 2013). According to a 2023 report by the PCD, food waste represents nearly 30% of the total solid waste produced in academic institutions, with 33% identified as inedible and 67% considered edible (PCD,2023). This aligns with the findings of Junsuthonpoj and Roswarn (2022), who examined food waste generation at Dusit Thani College in Thailand. Phosphorus (P) is an essential element for agricultural production, with over 90% of P-based fertilizers derived from phosphate rock (PR). However, PR reserves are unevenly distributed, with the majority concentrated in a few countries such as Morocco, China, and Egypt (USGS, 2024). In 2021, global P fertilizer consumption reached approximately 46 million tons, representing a 43% increase compared to year 2000 (FAO, 2023). Each year, the demand for P fertilizer grows, propelled by the expected expansion of the global population, which is forecasted to approach 10 billion by the year 2050 (UN DESA, 2015). This will necessitate increased food production to meet the nutritional demands of a growing global population and to advance the United

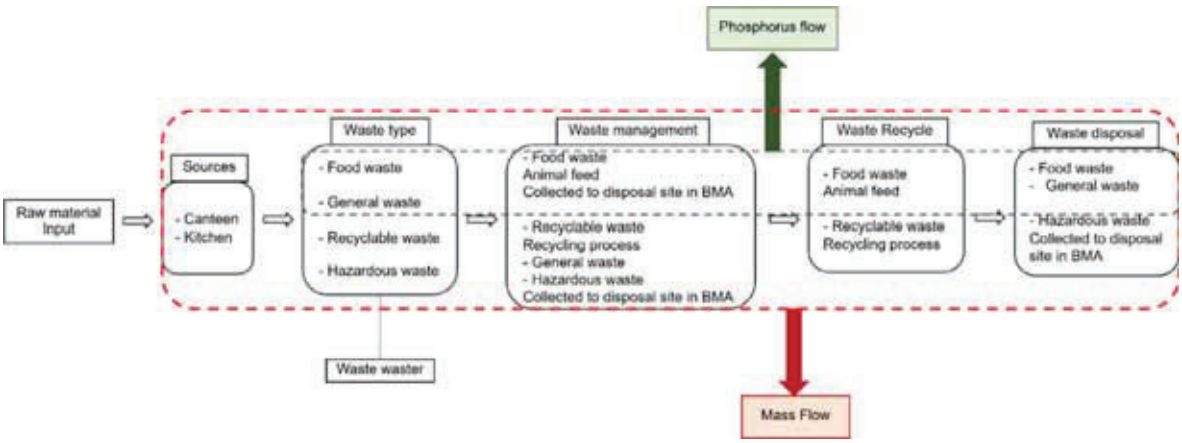

Fig. 1: System boundary for this study

Nations Sustainable Development Goal (UNSG)-2: 'End hunger, achieve food security and improved nutrition, and promote sustainable agriculture' (UN, 2022). Earlier studies have suggested that global phosphorus reserves could be exhausted in the next 50 to 100 years, creating a considerable danger to sustainable food security (Cordell *et al.*, 2009). This trend is not limited to the global scale; Thailand also faces a growing reliance on chemical fertilizers, importing approximately 200,000 tons of P fertilizer annually for agricultural use. The implementation of the Thai government's 'Kitchen of the World' policy is expected to contribute to a rise in phosphorus demand in Thailand over the next decade. Thailand's economy is largely influenced by agriculture, food exports, and tourism, which makes the sustainability of its P fertilizer supply vital for future growth. Accordingly, recovering phosphorus from organic urban waste—especially food waste—offers a viable strategy to reduce P imports and support the development of a nationwide circular economy. However, baseline data on the mass flow of phosphorus within the food waste system of Bangkok, Thailand remains limited, posing a significant barrier to the development of comprehensive and context-appropriate recovery strategies. This study explored the creation and features of food waste in educational establishments throughout Bangkok, mapping from the point of origin to ultimate disposal. A phosphorus mass flow diagram was being developed and analyzed to identify critical points of loss. Based on these findings, recommendations for practical phosphorus recovery measures within institutional food waste management are proposed. This study has been contacted in Bangkok, Thailand in 2022

MATERIALS AND METHODS

Bangkok, the capital city of Thailand, is characterized by its dense population and a high concentration of educational institutions, with 1,355 establishments offering various levels of education citywide. Nonetheless, because of constraints related to budget, personnel, and time, only three institutions were chosen and granted approval to act as sample sites. Notably, the decision to restrict the sampling period to three consecutive days facilitated the approval process. In conjunction with food waste, multiple additional datasets were compiled to create a complete system boundary for this analysis, as depicted in Fig. 1.

Primary school (AI1)

A primary school in Bangkapi District, comprising 2,985 students and 137 teachers, was investigated. At this institution, students were not involved in selecting their meals; the menu was predetermined by kitchen staff. The cook at the primary school had the duty of crafting breakfast and lunch menus, which have a direct impact on the amount of food prepared and the potential for waste production. This centralized strategy could have caused inconsistencies between the sizes of portions and what is actually consumed, especially regarding student meal preferences, thus leading to inevitable food waste. Food waste

generated at the institution was categorized into two types: uncooked food waste (UCFW), and cooked or post-consumption food waste (CFW). Only cooked or post-consumption food waste (CFW) was recycled for use as fish feed, while UCFW was disposed of as general waste stream. The school not only managed food and general waste streams but also sorted recyclable materials. General waste was disposed of in a landfill, while, recyclable materials were sold to a local recycling facility.

Technological college (AI2)

A technological college in Nongkhaem District was examined under the auspices of the Office of the Vocational Education Commission. As of 2023, the institution comprised 3,266 students and 153 teachers and staff members. Two canteens operated within the college, providing three daily meals, i.e. breakfast, lunch, and dinner. Meals were cooked on the premises and provided for students to select and purchase their meals. The canteens served a diverse range of food options, including à la carte dishes, snacks, beverages, and fruits. This self-selection food service approach granted students the freedom to choose, yet it could have impacted their eating patterns and the amount of food waste produced, influenced by the variety of the menu and portioning methods. However, the canteens did not practice systematic food waste segregation, except for specific materials such as eggshells, which were repurposed for plant nourishment. The waste management system at the college dealt with various types of waste, directing of general waste to a landfill, whereas recyclable materials were sold to a local recycling facility

Public university (AI3)

A public university located in Ratchathewi District and affiliated with the Ministry of Higher Education, Science, Research and Innovation (MHESRI) was selected for this study. The university faculty's canteen featured nine food stalls, each providing a diverse selection of food options, along with beverages. Breakfast and lunch services were provided to 916 students and 284 individuals comprising lecturers, staff, and external visitors. Furthermore, a local market fair provided food for sale; some people brought these meals into the canteen area and discarded the related leftovers and wastes within the same waste stream. During the sampling period, there was no practical food waste segregation in this canteen. Food waste was disposed of in the same stream as general waste, which was collected daily by the Bangkok Metropolitan Administration (BMA). Nonetheless, specific recyclable materials, especially PET bottles, were separated and sold to recycling vendors.

Data collection and sampling

Sampling was conducted over three consecutive weekdays at each academic institution, focusing on solid waste generated from kitchens or canteens. Conducting sampling over the weekend was not feasible due to the closure of the canteens during that period. While limiting the sampling period to weekdays ensured uniformity in food service operations, it may have constrained the representativeness of waste generation patterns across a full week. Food waste was classified into uncooked food waste (UCFW) and post-consumer or cooked food waste (CFW). The characteristics of food waste including bulk density (BD), moisture content (MC), total solids (TS), volatile solids (VS), fixed solids (FS), total Kjeldahl nitrogen (TKN), total phosphorus (TP), total organic carbon (TOC) and the carbon-to-nitrogen (C/N) ratio were analyzed according to Standard Methods (ASTM, 2016; APHA, 1998; Walkley and Black, 1934). Furthermore, the mass of solid waste was measured throughout the sampling procedure, and the waste management methods at every academic facility were recorded to support the assessment of phosphorus flow utilizing the mass balance concept. The phosphorus mass flow was then illustrated to identify the phosphorus losses within each academic institution's food waste management system. This visual illustration facilitated the measurement of phosphorus inputs, transformations, and outputs within different waste categories.

Data analysis

The mass flow of waste and phosphorus in food waste can be determined by utilizing data regarding the amount and percentage composition of waste, the per capita daily waste generation rate, and the phosphorus concentration found in food waste. These data points enabled the estimation of key parameters, including total phosphorus in food waste (P_{all}), phosphorus available for recycling ($P_{recycling}$), and phosphorus losses (P_{loss}). The calculations are detailed

through Eqs. 1 to 4. By embedding these components within the mass balance framework, this study seeks to suggest strategies for enhancing phosphorus recovery and decreasing phosphorus losses within institutional food waste system.

Eq. 1 calculated the percentage of waste generated daily in academic institutions (PCD, 2023):

$$Com_x = \frac{W_x}{W_T} \times 100 \quad (1)$$

Where;

Com_x = Percentage composition of type X waste (%)

W_x = Weight of type X waste (kg/day)

W_T = Total weight of waste in each academic institution (kg/day)

Eq. 2 was used to estimate the waste generation per student per day by dividing the total number of students (Mokjatturas *et al.,* 2025):

$$R_x = \frac{F_x}{S} \quad (2)$$

Where;

R_x = Rate of waste type X generation(g/student/day)

F_x = Weight of waste type X generation per day (g/day)

S = Total number of students in each academic institution (student)

The total student populations in AI1, AI2, and AI3 is 2,985, 3,266, and 916, respectively.

Eq. 3 was used to calculate the quantity of phosphorus present in each waste component (Mokjatturas *et al.*, 2025):

$$P_x = (WP_x) \times (C_x) \quad (3)$$

Where;

P_x = The quantity of P in waste type X (g P/day)

WP_x = Generation rate of waste type X containing phosphorus (kg/day)

C_x = Concentration of P in waste type X (g P/kg)

Eq. 4 was used to quantify the amount of phosphorus lost in each academic institution (Mokjatturas *et al.*, 2025):

$$P_{loss} = P_{all} - P_{recycle} \quad (4)$$

Where;

P_{loss} = Total mass of P in food waste that is sent to a landfill (g P/d)

P_{all} = Total mass of P present in food waste including UCFW and CFW (g P/d)

$P_{recycle}$ = Total mass of P in food waste that is not sent to landfills, e.g., food waste used as animal feed. (g P/d)

P loss is the amount of wasted or unused phosphorus, calculated by subtracting P recycled from P all.

This study used descriptive statistics to analyze and interpret the data, which consisted of the mean and standard deviation.

RESULTS AND DISCUSSION

Solid waste generation and management

In Fig. 2, the solid waste data obtained from the kitchens and canteens of three academic institutions is displayed, emphasizing differences in both volume and composition of the waste. The primary school (AI1) generated an average of 229 kg of solid waste per day, with food waste accounting for approximately 90% (206 kg). Most of this food waste was categorized as cooked food waste (CFW). This situation calls for deeper analysis to ascertain if the excessive waste was due to poor demand forecasting or inferior food quality. The school's management system employs contracted food vendors to prepare student meals, which has led to substantial leftovers. As a result of the dietary habits of young students, when the food served does not meet their tastes, they may either eat very little or leave it uneaten, which results in a large quantity of food waste being thrown away. Nevertheless, instead of disposing of CFW via landfill, AI1 repurposed it as animal feed. The average daily solid waste generated by the canteens of the technological college (AI2) and the public university (AI3) was approximately 71 kg and 40 kg daily, respectively. Food waste proportions (UCFW + CFW) from canteen operations in AI2 and AI3 were approximately 40–50% lower than those observed in AI1, resulting in a higher proportion of general waste in AI2 (54%). This discrepancy is likely attributable to the commercially operated nature of the canteens in AI2 and AI3, where economic considerations (including cost efficiency and customer satisfaction) significantly impact food preparation and portioning. In contrast,

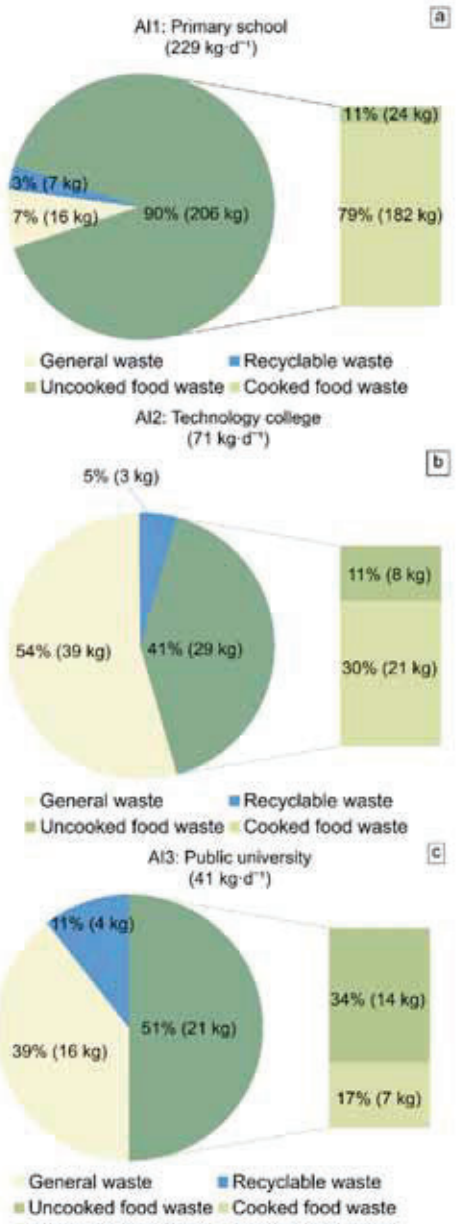

Fig. 2: Percentage of solid waste generation

AI1's vendor-hired meal service model lacks market-driven responsiveness, which may result in less adaptable meal offerings and higher rates of uneaten food. Interestingly, AI3 exhibited a higher proportion of recyclable waste (11%) compared to AI2 (5%) and AI1 (3%). Based on preliminary observations conducted over three sampling days, AI3 demonstrated more meticulous sorting of recyclable materials compared to the other two institutions.

According to the calculations, the daily average food waste per student at the three schools is 69 g (AI1), 9 g (AI2), and 23 g (AI3), respectively. AI1 exhibited the highest rate of food waste generation, suggesting significantly lower consumption efficiency compared to the other institutions. The most plausible explanation is that meals were centrally prepared by the primary school. Students were excluded from the meal selection process; the menus were set in advance

by the kitchen and school staff. Menus were developed in accordance with nutrition principles, while food portions were adjusted to comply with institutional budget. Consequently, a high volume of food leftovers may be attributed to students aged 3–12 years, who tend to discard meals that do not align with their preferences. This observation is consistent with the findings of Aorgart and Pinyoanuntapong (2017), who investigated the food consumption behaviour of preschool children aged 4-6 years in schools under the Bangkok Metropolitan Administration. Their research found that the majority of children did not take pleasure in consuming vegetables, despite parents' attempts to enhance their taste, including the preparation of deep-fried vegetable dishes. Moreover, the foods regularly consumed by children were closely associated with the menus prepared by their parents. Household dietary habits presumably influenced the development of children's food preferences, which may, in turn, affect meal acceptance and food waste levels within institutional settings. Furthermore, the 2017 Population Food Consumption Behaviour Study and the 2021 Population Health Behaviour Study revealed that food purchasing behaviour was strongly driven by personal preferences and desires, particularly among the 6–14-year-old age group, corresponding to childhood (NSO, 2018; 2021). In AI2 and AI3 institutions, per capita food waste generation was comparatively lower, potentially due to the availability of multiple food stalls that allowed individuals to select meals aligned with their personal preferences. This capability to select probably helped boost meal satisfaction, elevate consumption rates, and decrease leftovers. Across all three academic institutions, analysis of waste generation and management revealed that food waste constituted the largest fraction of total solid waste from the canteens. The majority of food waste generated in AI1 and AI2 institutions was classified as CFW, whereas AI3 exhibited a higher proportion of UCFW relative to CFW (Fig. 2). The study showed that the average food waste per person per day range from 9 to 69 g, with UCFW contributing between 2 and 8 g, and CFW between 7 and 61 g. Total solid waste generation per person per day varied from 22 to 77 g. A prior study conducted by Derqui *et al*. (2018) regarding food waste production in the cafeterias of similar academic institutions indicated that the daily food waste per individual varied between 60 to 100 g. The majority of this waste was classified as plate waste, accounting for 21–47 g in primary schools and 24–88 g in secondary schools. Gebreeyessus *et al.* (2019) reported that Kotebe Metropolitan University in Ethiopia generated predominantly food waste, accounting for 84% of total solid waste. The average daily food waste generation was 302 kg, with the largest portion originating from cafeteria operations at a rate of 0.093 kg per capita per day. García-Herrero *et al.* (2019) reported that primary school students generated an average of 136 g of food waste per day, while nursery school students generated 149 g, representing approximately 20–29% of the meals served. Similarly, Armington *et al.* (2020) found that CFW generation ranged from 13 to 25 kg/y in two K-12 schools and from 225 to 480 kg/y in three universities located in New York State. At the same time, Kasavan *et al*. (2021) explored food waste in ten school canteens and found an average waste production of 101 kg/d, corresponding to 12.2 g/capita/d. In contrast, Zhang *et al.* (2021) found that university students produced 406±337 g of food waste daily, amounting to approximately 53,000 tons annually. Fillimonau *et al.* (2022) examined food waste generation in private and public kindergartens in Russia, reporting waste volumes of 5 kg and 94 kg/d, respectively. In both cases, CFW accounted for up to 60% of the total food waste. In many regions, food waste generated by government agencies, public institutions, and private businesses is predominantly disposed of in landfills. This activity plays a major role in harming the environment, since the breakdown of organic waste emits methane, a powerful greenhouse gas, and hastens the reduction of landfill space. In 2016, the canteen at Chulalongkorn University in Thailand generated approximately 468 tons of food waste annually, all of which was repurposed as fish feed as part of a sustainable waste management initiative (Sukma *et al.* 2022). Additionally, Petchoo *et al*. (2022) examined meal quality and plate waste in kindergarten and elementary schools in Southern Thailand. According to the study, the typical daily plate waste amounted to 71 g per kindergartener and 32 g per elementary student, resulting in estimated economic losses of approximately 86 USD and 15 USD per day, respectively. Sena Sağlam and Aydın (2024) examined the generation of solid waste in several academic institutions in Istanbul and discovered that organic waste represented the highest percentage at 36.4%, with individual generation rates fluctuating from 17 to 37 g per person per day. Similarly, Du *et al.* (2024)

Table 1: Chemical characterization of food waste from three academic institutions

Category	Parameters (Unit)								
	BD (kg/m^3)[a]	MC (% w/w)[a]	TS (mg/g)[a]	VS (%TS)[b]	FS (%TS)[b]	TP (mg/g)[a]	TKN (mg/g)[b]	TOC (% w/w)[b]	C/N ratio
Academic institution 1: School									
UCFW	284	91	90	93	6.9	0.09	31	37	11.4
CFW	796	75	252	91	8.9	0.76	34	35	10.2
Academic institution 2: College									
UCFW	226	86	140	64	36	0.28	19	24	12.9
CFW	736	70	270	96	4.0	0.53	27	36	13.2
Academic institution 3: University									
UCFW	221	93	74	85	15	0.29	26	30	12.1
CFW	860	78	219	89	11	0.61	30	34	11.5

[a] = wet basis
[b] = dry basis

reported an average daily food waste generation of 85 g per person, underlining the significance of organic waste as a dominant component in institutional settings.

Characterization of uncooked and cooked food waste

Table 1 shows that UCFW generated by three academic institutions exhibited a bulk density (BD) ranging from 221 to 284 kg/m^3, whereas CFW samples showed substantially higher values between 736 and 860 kg/m^3. The moisture content of UCFW samples was notably higher, ranging from 86% to 93%, compared to 70% to 78% in CFW. The primary reason for this difference is the larger share of fresh vegetables and fruits included in UCFW. Total solids (TS) in UCFW samples ranged from 73 to 140 milligrams per gram (mg/g), with volatile solids (VS) comprising 64%–93% of TS. By contrast, CFW samples showed higher TS values between 219 and 270 mg/g, with VS accounting for 89%–96% of TS, indicating a higher organic proportion. Additionally, total phosphorus (TP) content was lower in UCFW samples (0.09–0.29 mg/g) compared to CFW (0.53–0.76 mg/g), as presented in Table 1. Similarly, total Kjeldahl nitrogen (TKN) levels were higher in CFW (27–34 mg/g) than in UCFW (19–31 mg/g). The total organic carbon (TOC) content in UCFW samples ranged from 24% to 37%, whereas CFW samples exhibited a narrower range of 34%–35%. However, the C/N ratios of both UCFW and CFW samples were comparable, ranging from 10 to 13. The evaluation of phosphorus and nitrogen recovery potential from food waste relies heavily on these chemical parameters. A comparison of the measured values with those reported in previous studies is depicted in Table 2.

P flow in food waste

Table 3 summarizes the mass balance of phosphorus across three academic institutions, while Fig. 3 illustrates the schematic mass flow developed in this study. For AI1, as shown in Fig. 3a, the phosphorus content of UCFW and CFW samples was 0.09 and 0.76 mg/g, respectively. Based on daily waste generation rates, the total phosphorus mass from both waste types was calculated at 141 g/day, corresponding to an annual total of 28 kg (assuming 200 school days). UCFW provided 2.3 g/day, whereas CFW represented the majority with 139 g/day. Since AI1 sells its CFW to farmers for use as fish feed, this practice represents a phosphorus recycling mechanism. Consequently, the total phosphorus loss from AI1's food waste system was restricted to 0.4 kg annually. For the technology college (AI2), as illustrated in Fig. 3b, the measured phosphorus contents in UCFW and CFW were 0.28 mg/g and 0.53 mg/g, respectively. These values correspond to a total phosphorus mass of 14 g/day, with contributions of 2.3 g/day from UCFW and 11.2 g/day from CFW. AI2's phosphorus loss was calculated to be 2.7 kg annually, since all food waste was directed to landfills without undergoing recycling. At the public university (AI3), shown in Fig. 3c, the measured phosphorus content in UCFW and CFW samples was 0.29 mg/g and 0.61 mg/g, respectively. The total phosphorus mass generated in the canteen was approximately 7.9 g/day, comprising 3.9 g/day from UCFW and 4.0 g/day from CFW, equating to 1.6 kg/year based on an operational assumption of 200 school days. Similar to AI2, phosphorus loss from UCFW and CFW at AI3 was estimated at 1.6 kg/y, attributed to landfill disposal without recycling intervention. These conclusions underscore that the retention of phosphorus

Table 2: Comparative overview of food waste characteristics in this study with other studies.

Waste	Parameters (Unit)									Sources
	BD (kg/m³)[a]	MC (%w/w)[a]	TS (mg/g)[a]	VS (%TS)[b]	FS (%TS)[b]	TP (mg/g)[a]	TKN (mg/g)[b]	TOC (%w/w)[b]	C/N ratio	
Mixed FW	-	-	80.68	-	-	0.93	-	-	-	Ratanatamskul *et al.* (2014)
Mixed FW	-	-	189	93	-	1.85	-	-	21.3	Zhang *et al.* (2015)
Mixed FW	-	-	310	88.71	-	1.07	-	-	-	Huiru *et al.* (2019)
Mixed FW	-	59.70	-	-	-	12.58	-	-	-	Aminzadeh *et al.* (2021)
Mixed FW	-	-	310.52 – 419.51	19 – 78	-	5.69 – 16.75	-	-	9.81 – 12.50	Al-samet *et al.* (2021)
CFW	-	54.23	457.7	-	-	1.45	20.2	34.82	17.24	Chaher *et al.* (2021)
Mixed FW	-	77.40	226	-	-	1.08	-	-	18.35	Chaher *et al.* (2022)
Mixed FW	-	74.00	260	94.23	-	1.29	-	-	17.10	Chaher *et al.* (2023)
CFW	-	75.80	242	98.3	-	1.09	30.1	-	-	Pimpeach *et al.* (2023)
CFW	-	72.75	272.53	94.66	5.34	0.43	20.5	21.09	10.29	Khaita *et al.* (2024)
UCFW	221 -284	86 – 93	74 – 140	64 – 93	6.9 – 36	0.09 – 0.29	19 – 31	24 – 37	11 – 13	This study
CFW	736 – 860	70 – 78	219 – 270	89 – 96	4.0 – 11	0.53 – 0.76	27 – 34	34 – 36	10 – 13	

[a] = wet basis
[b] = dry basis

Table 3: Data for P flow in academic institutions

Flow	In		Total waste	Loss	
	UCFW	CFW		UCFW	CFW
Primary school: AI1					
P Concentration (g/kg)	0.09	0.76		0.09	-
Total waste (kg/d)	24	182	206	24	-
P mass (g/d)	2.3	140	142	2.3	-
P mass (kg/year)	0.4	27.8	28.3	0.4	-
Technology college: AI2					
P Concentration (g/kg)	0.28	0.53		0.28	0.53
Total waste (kg/d)	8	21	29	8	21
P mass (g/d)	2.3	11.2	13.5	2.3	11.2
P mass (kg/year)	0.5	2.2	2.7	0.5	2.2
Public university: AI3					
P Concentration (g/kg)	0.29	0.61		0.29	0.61
Total waste (kg/d)	14	7	21	14	7
P mass (g/d)	3.9	4.0	7.9	3.9	4.00
P mass (kg/year)	0.8	0.8	1.6	0.8	0.8

in food waste systems is intricately connected to the establishment of recycling systems in academic settings. Although the estimated phosphorus loss from a single institution may appear minor on a mass basis, more than 1,400 academic institutions operate within the Bangkok Metropolitan area. The estimated annual phosphorus loss, when extrapolated, ranges from 86–1,959 kg for 437 schools, 8–82 kg for 83 colleges, and 587–901 kg for 88 universities. Thitanuwat *et al.* (2016) reported that if phosphorus contained in food waste across Bangkok is not recovered, the total annual loss could reach up to 5,337.3 tons. These findings highlight the strategic role of academic institutions in the Bangkok Metropolitan Area as key locations for waste sorting and phosphorus recovery.

Environmental and economic benefits of phosphorus recovery through composting

This segment evaluates the environmental and economic gains associated with phosphorus recovery through composting. Composting was selected as the organic fertilizer method due to the favorable characteristics of food waste, including moisture content ranging from 55% to 80%, organic matter between 75% and 98%, bulk density of 706–860 kg/m³, and a carbon-to-nitrogen (C/N) ratio between 7.5 and 18.5 (Selvam *et al.*, 2021). Food waste can be processed alongside other organic materials, including

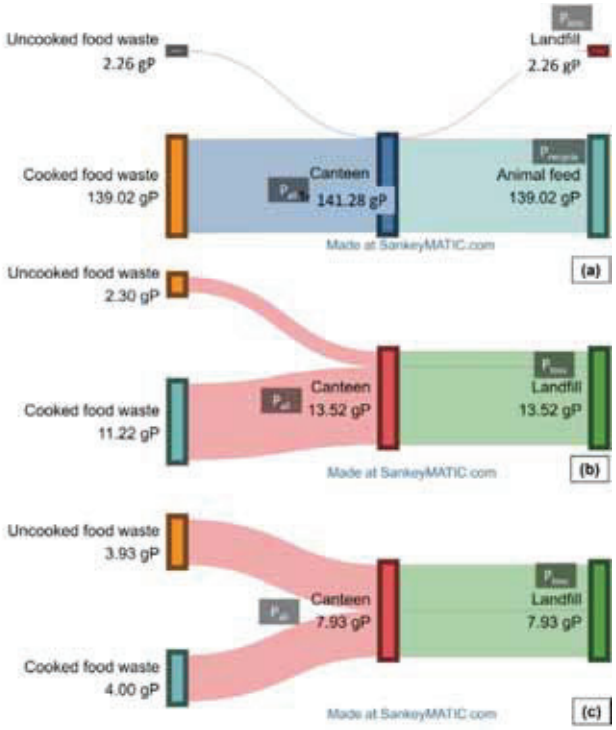

Fig. 3: The daily P flows in a primary school (a), a technology college (b), and a public university (c)

agricultural waste and tree-trimming debris, which usually tend to have lower moisture content. This blend improves the overall moisture balance and structural integrity of the composting matrix. Table 4 presents the estimated cost savings associated with diverting food waste to composting rather than landfill disposal. According to the Bangkok Metropolitan Administration (BMA), the cost of solid waste collection from the source to a transfer station approximately 7.5 United States Dollars per cubic meter (USD/m^3), while landfill disposal incurred an additional 7.7 USD/m^3 (DOE, 2021). The expense associated with moving solid waste from transfer stations to landfill locations varied based on the location. For the Nong Khaem, On Nut, and Sai Mai transfer stations, the respective transportation costs were approximately 21.3, 22.1, and 24.6 USD/ton, respectively (SERI, 2023). The waste collection costs for AI1 and AI3 were based on a rate of 22.1 USD/ton, corresponding to service coverage at the On Nut transfer station. In contrast, AI2's collection cost was calculated at 21.3 USD/ton, reflecting waste transfer via Nong Khaem station. Irrespective of the collection site, the cost of transporting from the transfer station to the landfill was uniformly assessed at 22.7 USD/ton. All USD costs in this study were calculated referring to the exchange rate of 1 USD =32.463 Baht on October 1, 2024.

Notably, the estimated expenditure for food waste (UCFW and CFW) collection, transfer, and disposal at AI1 ranged from 1,395 to 1,870 USD/year, assuming CFW was not diverted for animal feeding. Conversely, it was anticipated that AI2 and AI3 would face annual disposal costs estimated at roughly 208–321 USD, respectively. When scaled to the institutional landscape of Bangkok, the total cost for academic institutions was estimated between 100,185 and 833,595 USD/year under current conditions, with a projected increase to 138,513–1,145,088 USD/year in future scenarios. These financial outlays were regarded as significant. Crucially, channeling all food waste into composting could markedly decrease expenses linked to landfills. In addition, compost-derived fertilizer offers agricultural benefits by supplying plant-available P. The phosphorus content of the organic fertilizer was calculated post-composting. Composting yields were estimated based on an initial carbon-to-nitrogen (C/N) ratio of 25. The amount of yard waste needed for co-composting and the resulting fertilizer production

Table 4: Feasibility Environmental and financial benefit assessment of phosphorus recovery from food waste using composting approach

Items	Cost saving of solid waste collection and disposal (USD)			Composting	
	Waste volume (m^3/year)	Food waste management cost for landfilling (USD/year)[b]		Total waste (kg (wet basis) /year)	Yield of compost (kg (wet basis) /year)[c]
		Current	Future		
The primary school (AI1)					
UCFW	16.9	237	365	4,800	1,079
CFW[a]	45.7	1,158	1,505	36,400	18,967
Total cost		1,395	1,870	Total yield	20,046
The total school under Bangkok Metropolitan Administration (BMA) (437 schools, 253,554 students)					
UCFW	1,663.6	22,021	34,579	405,686	87,696
CFW	3,879.5	100,076	129,359	3,093,359	1,381,038
Total cost		122,097	163,938	Total yield	1,468,734
The technology college (AI2)					
UCFW	7.1	92	149	1,600	340
CFW	5.7	136	181	4,200	1,731
Total cost		*228*	*330*	Total yield	*2,071*
The total college in Bangkok under Office of the Vocational Education Commission (83 colleges, 92,257 students)					
UCFW	151.3	2,004	3,148	36,903	7,977
CFW	162.0	4,179	5,401	129,160	57,664
Total cost		6,183	8,549	Total yield	65,641
The public university (AI3)					
UCFW	12.7	162	260	2,800	543
CFW	1.6	46	61	1,400	551
Total cost		208	321	Total yield	*1,*094
The total university in Bangkok under Ministry of Higher Education, Science, Research and Innovation (88 university, 888,622 students)					
UCFW	10,932.1	144,687	227,195	2,665,866	576,274
CFW	1,783.2	45,999	59,459	1,421,795	634,764
Total cost		190,686	286,654	Total yield	1,211,038
Total educational institutions in Bangkok area (1,355 educational institutions, 1,495,232 students)					
UCFW	2,452.6–18,394.8	32,463–243,453	50,976–382,281	598,093–4,485,696	129,288–969,662
CFW	2,625.4–22,878.1	67,722 – 590,142	87,537 – 762,807	2,093,325 – 18,241,830	934,570–8,144,112
Total cost		100,185–833,595	138,513–1,145,088	Total yield	1,063,858–9,113,774

[a]Calculation of CFW in case it is not given away for animal feeding. [b]Solid waste collection and disposal costs for sanitary landfills operated by BMA (DOE, 2021). The October 1, 2024, exchange rate was 1 USD =32.463 Baht. [c]omposting of a mixture of food and green waste (Thitanuwat *et al.,* 2016) to achieve an optimum. C/N ratio of 25. The composting process yields 11% of the mixture as organic fertilizer (Keng *et al.,* 2020).

were assessed using the approach detailed by Keng *et al*. (2020), as illustrated inTable 3. The CFW from AI1 yielded up to 19 tons of fertilizer per year, followed by AI2 at 1.7 tons annually. When extrapolated to Bangkok's academic sector, schools could produce as much as 1,469 tons of fertilizer annually, with universities and colleges contributing approximately 1,211 tons and 65 tons, respectively. If food waste from every academic institution be allocated to composting, the projected annual compost yield is estimated to be between 1,064 and 9,114 tons, featuring a phosphorus concentration of roughly 1.04–1.58%. The estimated composting strategy demonstrated the capacity to reduce phosphorus loss by 132–11,553 kg annually. According to the assessment, the disposal, collection, and transportation of food waste could result in cost savings of approximately 100,185–833,595 USD per year under the current scenario, with projected future savings ranging from 138,513–1,145,088 USD annually. Furthermore, educational institutions in

Bangkok could work together to create an annual output of organic fertilizer ranging from 1,064 to 9,114 tons through composting efforts. At Srinakharinwirot University, approximately 400 kg/day of cafeteria food waste was assessed as a co-substrate for biogas production alongside domestic wastewater. Given a biogas plant with an operational capacity of 35 tons per day, the system is expected to yield annual profits amounting to 905,646 USD, which accounts for 46.3% of the total revenue (Koido *et al.,* 2018). Similarly, Sakcharoen *et al.* (2021) analyzed 60 kg/day of food waste from Chulalongkorn University canteens for co-digestion with wastewater sludge. The study reported total economic benefits of 8,541 USD/year, including 104 USD/year in sludge treatment cost savings and an additional 4,800 USD/year attributed to space utilization efficiency. At Kaen University, 39.2 tons of food waste were recorded annually. Composting this waste with wood chips resulted in a reduction of disposal costs by 27,164 USD per year and yielded approximately 13,377 kg of organic fertilizer (Mu *et al.,* 2017). A study carried out by Sikhao *et al*. (2023) investigated the practices of food waste management in secondary schools, where nearly 180 liters of food waste were produced on a daily basis. The study analyzed three methods of treatment: composting, microbial decomposition, and biogas production. Among these, composting with dung manure yielded the highest economic return, generating a weekly profit of 140 USD.

CONCLUSION

According to the data collected in 2021 (PCD, 2022), food waste accounted for more than 40% of total solid waste in the Bangkok metropolitan area. Insufficient management of food waste persists, notably in the sectors of collection, transportation, and disposal. Furthermore, research on the material flow of food waste and the associated phosphorus content remains limited in scope. A considerable amount of food waste originates from academic institutions, attributed to their nearly continuous food consumption throughout the day. In this study, food waste was categorized into uncooked food waste (UCFW) and cooked food waste (CFW). Uncooked food waste is defined as the waste of raw materials, which encompasses vegetable and fruit peels, roots, stems, leaves, and eggshells. Conversely, cooked food waste (CFW) includes the remnants left on plates post-meal, commonly termed as “leftovers”. The results showed that food waste composition from academic institutions in this study ranged from 40% – 90% of total solid waste. This variation appears to be influenced by the level of education. Additionally, primary schools, which adopt centralized food preparation techniques, demonstrated a much greater amount of plate waste in comparison to college and university dining facilities. The chemical characteristic of food waste in this study showed that cooked food waste has higher nutrients (nitrogen and phosphorus) concentrations than uncooked food waste. The assessment of P flow illustrated that annual phosphorus inputs into the system ranged from 1.6 to 28.3 kilograms. Across the three academic institutions studied, phosphorus losses were estimated between 0.4 and 2.7 kilograms per year, representing 11% to 100% of the total phosphorus entering the system. While the primary school accounted for the greatest quantity of food waste in the study, it was revealed that only 11% of this waste was actually discarded. This low proportion is attributed to effective waste segregation practices, wherein food waste was separated from other waste streams and subsequently recycled. Specifically, the sorted excess food was sold to fish farmers for incorporation as fish feed, an approach that is both resource-efficient and economically rewarding. This practice not only reduced phosphorus loss from the food waste stream but also provided income-generating opportunities for the institutions involved. Composting acts as a practical approach to reclaim phosphorus, yielding benefits for the environment and the economy. For instance, based on institutional waste volumes, landfill disposal costs could be reduced by approximately 1,395 to 1,870 USD per year for a primary school (AI1). In addition to cost savings, composting transforms food waste into nutrient-rich organic substance. This contributes to the circular management of phosphorus resources and is also in accordance with the national goal for reducing waste sustainably. Additionally, fertilizer-like product yields from food waste could reach approximately 19 tons per year. When extrapolated to food waste generated by all academic institutions in Bangkok, projected cost savings could range from 100,185 to 833,595 USD annually under the current scenario (representing 0.05–0.4% of the total cost). Under a future, more optimized scenario, annual savings could increase to between 138,513 and 1,145,088 USD. These initiatives would support the creation of around 1,064 to 9,114

tons of fertilizer-like products each year, possibly decreasing the import of phosphorus-based fertilizers by an estimated 0.5–5% annually. However, the success of composting depends on the implementation of proper waste sorting and management practices. Alongside composting, the efficient sorting of food waste aids in alternative waste processing techniques, such as its application in animal feed and its decomposition in anaerobic digestion, allowing for the recovery of significant amounts of phosphorus fertilizer crystals and the production of methane gas as a renewable energy source. The outcomes of this study revealed the financial relevance and ecological benefits of embracing sustainable waste management approaches within academic settings. Redirect food waste to composting not only reduces expenditures associated with landfill disposal but also contribute to resource circular economy practice through the production of phosphorus-rich fertilizer substitutes.

AUTHOR CONTRIBUTIONS

S. Chinwetkitvanich, the corresponding author, has contributed to the conceptualization, design of methodology, data verification, discussed the results, and finalized the manuscript. S. Mokjatturas has performed conducting a research and investigation process, data collection, data curation and interpretation, and manuscript preparation. W. Patthanaissaranukool has prepared the conceptualization, design of the methodology, and discussed the results. S. Polprasert has contributed to the conceptualization, design of methodology, and discussed the results. Recep Kaan Dereli has performed discussed the results and manuscript editing. The results were evaluated by all authors, and the final version of the manuscript was approved.

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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

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ABBREVIATIONS

%	Percent
AI	Academic institution
AI1	Primary school
AI2	Technological college
AI3	Public university
BD	Bulk density
BMA	Bangkok Metropolitan Administration
C/N	Carbon-to-nitrogen
CFW	Cooked food waste
CO_2	Carbon dioxide
COVID-19	Coronavirus Disease 2019
FW	Food waste
FS	Fixed solids
g	Grams
G	Giga
GHG	Greenhouse gases
h	Hours
kg	Kilogram
m^3	Cubic meter
MC	Moisture content
$MtCO_2e$	Million Tons of carbon dioxide equivalent
Pall	Total phosphorus in food waste
Ploss	Phosphorus losses
Precycling	Phosphorus available for recycling
P	Phosphorus
PCD	Thailand's Pollution Control Department
PR	Phosphate rock
t	Ton
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TS	Total solids
UCFW	Uncooked food waste
UN	United Nations
UNEP	United Nations Environmental Protection
UNSG	United Nations Sustainable Development Goal
USD	United States Dollar
USD/m^3	United States Dollars per cubic meter
VS	Volatile solids
y	Year

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CASE STUDY

Fate and dynamics of microplastics in the municipal waste composting process

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study demonstrates stage-specific changes in microplastic abundance and polymer composition throughout composting, highlighting process-based reduction and fragmentation dynamics as a novel contribution from Indonesia. The study aimed to explore the dynamics of microplastic presence throughout the composting process of municipal waste and to evaluate the effectiveness of composting in mitigating microplastic contamination in compost derived from municipal waste.

METHODS: Sampling was conducted during five consecutive stages of composting at the Galuga landfill composting facility. The stages included three-week fermentation material, dried products, shredded material, grinded material, and compost products ready for sale. The extraction and identification techniques followed standardized protocols. The study integrated biological digestion and density separation methods, implementing rigorous measures to reduce cross-contamination.

FINDINGS: A total of 5042 microplastic particles were identified from approximately 25 kg of samples, yielding an average abundance of 201.53 ± 14.02 particles per kilogram. Microplastic concentrations exhibited no notable variations between samples gathered during the wet and dry seasons. A progressive reduction in microplastic levels was detected from the initial stage to the final outcome. The presence of larger microplastics (>2000 micrometers) diminished from the initial stages to the finished product, whereas smaller microplastics (200 to 1000 micrometers) increased from the beginning to the compost product. Fragments were noted as the most widespread shape of microplastics, predominantly resulting from mixed waste packaging. Eight different types of polymer groups were identified, with polyethylene, polypropylene, and polystyrene being the most prevalent, comprising 72.10 percent.

CONCLUSION: The results indicate evident stage-specific variations in the occurrence of microplastics throughout the composting process of municipal waste. The abundance of microplastics consistently decreased from initial materials to the final compost product, with significant reductions noted after the shredding and grinding stages. Even though larger fragments were prevalent throughout all phases, the proportion of smaller particles rose as the larger ones fragmented during the composting process. The polymer types dominated in this research reflect the high presence of food packaging in the incoming waste stream. This emphasizes the potential of composting as a mitigation approach and the critical need for enhanced upstream waste separation and more stringent regulations to decrease plastic inputs into composting systems.

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INTRODUCTION

Over the past three decades, issues related to plastic waste and microplastics have been identified in various ecosystems (Bakir *et al.,* 2024; Cordova *et al.,* 2025; Omeyer *et al.,* 2023; Rahman *et al.,* 2024). These studies have underscored the presence, distribution, and fate of microplastics, in addition to the complex detrimental effects at the population level throughout ecosystems (Bakir *et al.,* 2024; Cordova *et al.,* 2025; Omeyer *et al.,* 2023; Rahman *et al.,* 2024; Utari *et al.,* 2024; Nakano *et al.,* 2025). Microplastics have been proven to be one of the factors causing imbalance in the system between soil, plants, and microbes living in these areas (Jia *et al.,* 2024; Wang *et al.,* 2024). Nonetheless, this is significant and pertains to the production of plant biomass (Ingraffia *et al.,* 2022). Microplastics have demonstrated an impact on soil microbial communities, frequently leading to a decrease in overall diversity while encouraging taxa linked to nitrogen fixation and urea degradation (Wang *et al.,* 2024). This increases the dominant microbial biomass, which negatively impacts the development of soil fauna such as earthworms and other nematode species (Liu *et al.,* 2023). Among the various pathways through which microplastics enter agricultural land, fertilizers and compost present a particularly intriguing area of study, especially as the use of fertilizers and compost is experiencing a resurgence in organic farming (Ruffell *et al.,* 2025; Steiner *et al.,* 2023; Weithmann *et al.,* 2018; Zhang *et al.,* 2024). Compost, derived from the decomposition of organic matter, serves as a soil amendment capable of enhancing its physical, chemical, and biological properties, thereby supporting healthier plant growth (Riaz *et al.,* 2021; Ozores-Hampton *et al.,* 2021). The composition of compost is is influenced by the quality of its raw organic materials, which play a significant role in its makeup (Ozores-Hampton *et al.,* 2021; Riaz *et al.,* 2021). Compost can commonly be used in various agricultural, horticultural, and landscaping applications (Ozores-Hampton *et al.,* 2021). The composting process has four main phases (Soni and Devi, 2022). The first is the mesophilic phase, which involves temperature and mesophilic microorganisms to degrade organic material. Next is the thermophilic phase, where temperature increases with the help of thermophilic microbial metabolism. The organic raw material's temperature naturally declines, entering the cooling phase, thereby permitting mesophilic microorganisms to persist in the decomposition process (Soni and Devi, 2022). In the final phase, maturation occurs, and the compost is ready for use to improve soil quality. Compost products improve soil structure, water retention, and nutrient content. Proper use of compost products promotes healthier plant growth (Ozores-Hampton *et al.,* 2021; Riaz *et al.,* 2021). In Indonesia and most countries in the Global South, proper waste sorting has not been fully implemented (Cottom *et al.,* 2024). Consequently, the presence of heavy metals, microplastics, and additional contaminants leads to contamination (Zaib *et al.,* 2023). These contaminants can reduce soil quality, disrupt plant growth, and pose health risks (Premarathna *et al.,* 2023). Studies on plastic and microplastic content in fertilizers and compost began in 2012 for plastic contamination and in 2018 for microplastic occurrence (Porterfield *et al.,* 2023; Weithmann *et al.,* 2018). In Indonesia, studies began with microplastic occurrence in agricultural land and indicated that fertilizers and compost are two of the sources (Iswahyudi *et al.,* 2024). Generally, the presence of microplastics in compost products is recognized (Alashti *et al.,* 2025; Berset and Stoll, 2024; Sholokhova *et al.,* 2023). A significant number of studies prioritize the quantification of microplastics found in compost products, instead of grasping the dynamic alterations that happen throughout composting. As a result, the fate of microplastics during the composting process is less well-understood. Unlike previous studies (Berset and Stoll, 2024; Porterfield *et al.,* 2023; Sholokhova *et al.,* 2023; Weithmann *et al.,* 2018) that only quantified microplastics in compost end-products, the current work demonstrates process-level dynamics, showing fragmentation and polymer-specific changes during composting. Given these interactions, this study focuses on how microplastic abundance and characteristics shift across composting stages and whether composting reduces microplastic contamination. This might serve as a means to alleviate microplastic contamination in the process. This study presents two hypotheses. The primary hypothesis posits that there will be a notable reduction in microplastic concentration throughout the composting process, transitioning from the the initial fermentation stage to the final compost product. Another hypothesis posits that composting facilitates fragmentation, which causes a shift in

the distribution of microplastic sizes toward smaller particles. The aims of this study are to investigate the dynamics of microplastic occurrence during the composting process of municipal waste and to assess the potential for composting to reduce microplastic contamination in municipal waste-based compost. This study has been carried out at the compost house in the Galuga landfill area, Indonesia in 2024.

MATERIALS AND METHODS

Study area

The Galuga landfill (Fig. 1) covers an area of 42.7 hectares (ha). Since 1992, the local administrations of Bogor City and Bogor Regency in Indonesia have overseen its operations. The landfill receives 1,100 tons of waste daily, comprising 500 tons from Bogor City and 600 tons from the Bogor Regency. The waste is categorized as mixed, with 76 percent (%) classified as organic waste, 19% as plastic, 4% as paper, and 1% as other refuse. Currently, the Galuga landfill utilizes open disposal methods, but plans are in place to transition to a controlled landfill. The organic waste composting facilities at this location are currently not operating at the optimal capacity of the landfills, which ranges between 100 and 500 kilograms (kg) per day. The composting process at the Galuga Landfill Compost Facility begins with the segregation of mixed waste received from garbage trucks, categorizing it into two distinct groups: organic and inorganic waste. The organic waste is subsequently mixed with a fermenting agent, specifically sawdust. This fermentation phase lasts for three weeks. Following fermentation, the organic material is subjected to a two-day drying process under sunlight. The subsequent step entails sifting through the compost material to distinguish the inorganic waste

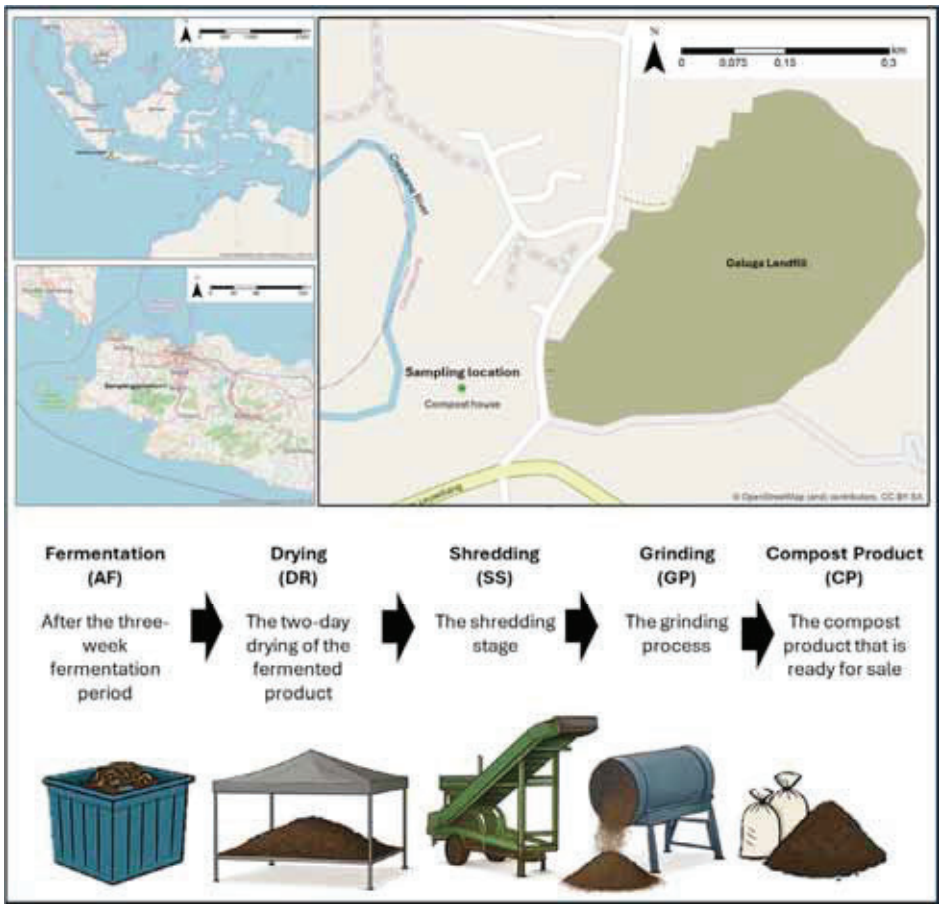

Fig. 1: Geographical location of the study area along with the sampling locations in Galuga Landfill area and schematic diagram of the composting process

elements. After filtration, the compost is ground to reduce its particle size. The final compost product is then packaged in plastic for sale.

Field sampling

Samples are collected at various stages of the composting process to assess microplastic content (Fig. 1). Specifically, five samples and five replications, each weighing approximately 500 grams (g), are collected after the three-week fermentation period (AF), the two-day drying of the fermented product (DR), the shredding stage (SS), the grinding process (GP), and finally, from the compost product (CP) that is ready for sale. Samples were taken in January and July 2024. Samples collected in January reflected the rainy season, recording a total precipitation of 466 millimeters (mm), whereas samples obtained in July depicted the dry season with a total rainfall of 140 mm. These samples are collected using a stainless-steel shovel and stored in glass bottles with metal caps. The samples were stored in a sealed container at a temperature of 2-3 degree Celsius (°C) and processed within 24 hours (h).

Laboratory analysis

The laboratory procedures followed strict standardized protocols specifically developed to meticulously examine microplastics within biowaste and samples rich in organic matter (Nurhasanah *et al.,* 2021; Prosenc *et al.,* 2021; Steiner *et al.,* 2023; Steiner *et al.,* 2024). Upon arrival at the laboratory, all procedures were conducted under sterile conditions to prevent contamination. Compost samples were carefully transferred into pre-cleaned glass containers to ensure integrity. The process of extracting microplastics involved multiple stages: biological digestion, density separation, and detailed identification. This methodology, while rooted in previously established procedures, was specifically modified to enhance accuracy during the implementation phase. Initially, the compost samples were allocated into clean test tubes and dehydrated in a sterile oven maintained at a consistent temperature of 45°C for a period ranging from 48 to 72 h to eliminate all moisture, thereby preserving sample integrity effectively. Following the dehydration phase, Fenton's reagent, composed of 40 milliliters (mL) of 30% Merck Millipore Emprove® hydrogen peroxide (H_2O_2) and a concentration of 20 mL of 10 milligrams per milliliter (mg/mL) Merck Millipore Emsure® Iron(II) sulfate ($Fe(II)SO_4$), was introduced into the test tubes. This reagent significantly contributed in the decomposition of the biogenic components present in the samples. Subsequently, the samples were maintained in a controlled airflow environment overnight, before being subjected to repeated heating in a water bath at 45°C for a prolonged duration of 96 to 120 h. This combination of treatments facilitated the thorough decomposition of organic matter, allowing for more effective extraction of microplastics. After completing the digestion process, microplastics were isolated by utilizing a high-density zinc chloride (ZnCl2) solvent to differentiate based on density. This selective separation method allowed for the concentration of microplastic particles distinct from other organic and inorganic materials present in the samples. Once the residues were separated, they were placed onto sterile cellulose nitrate filter paper, where a detailed ocular examination of the sample took place. The particles that adhered to the filter were analyzed in detail using an Olympus CX31 microscope equipped with a IMX307 Sony Camera. All microparticles were categorized according to specific criteria: consistent shape, the absence of segmentation, and a clear lack of biological or cellular traits indicative of organic materials. In this study, the minimum detection threshold for microplastics was set at 200 micrometers (µm), slightly lower than the 212 µm limit reported in a previous investigation across four environmental matrices (Lao and Wong, 2023), thereby contributing valuable data. In the ongoing stage of the study, a significant 21.18% of the microplastic particles identified visually (1068 from a total of 5042) were carefully analyzed for their chemical composition through the use of attenuated total reflectance-fourier transform infrared (ATR-FTIR) spectroscopy. Chemical characterization was performed using an Agilent Cary 630 FTIR spectrometer fitted with a diamond ATR unit and operated through MicroLab Expert software. Microplastic particles subjected to analysis were selected via a systematic random sampling approach to ensure representativeness and representation of the compost product samples. The analysis uncovered that the tiniest microplastic particle identified was a notable 205.6 micrometers (µm), whereas the largest one showed a significant size of 4999.7 µm, thus emphasizing the wide variety

of sizes present within the sampled population. FTIR analysis was performed with a high degree of accuracy, achieving a resolution of 4 reciprocal centimeter (/cm) and comprising 32 individual scans across a spectral range from 650 to 3000/cm. The identification of polymers relied on a meticulous analysis of unique peak patterns found in different spectral regions, providing essential insights into the materials' composition. The chemical composition results obtained from FTIR analysis were compared against established polymer standard references from reputable institutions (Agilent, Thermo Scientific, and Shimadzu). Additionally, comparisons were made with the FTIR library of plastic particles (FLOPP) spectral library of plastic particles and standard references from University of Toronto and Thermo Fisher Scientific, ensuring a robust identification process.

Quality assurance/quality control

To minimize potential cross-contamination of microplastics during the study, stringent preventive protocols were implemented at every stage. Researchers adhered to rigorous personal protective measures, donning 100% cotton garments, medical masks, and latex gloves to maintain a sterile environment necessary for obtaining reliable results. All glassware and surgical instruments utilized were thoroughly pre-cleaned and rinsed with ultrapure water to eradicate any potential contaminants. Furthermore, sterile filtration paper was employed to purify all chemical solutions used, including H_2O_2, Fe(II) SO_4, and $ZnCl_2$, thereby ensuring the comprehensive removal of any residual microparticles. In an exemplary demonstration of methodological rigor, procedural blanks (5 observations) were incorporated; open glass beakers were strategically placed near the samples during the extraction phase, continuing through to the conclusion of the identification procedures. Significantly, there was no evidence of cross-contamination in the blank samples, which supports the the integrity and reliability of the research methodology applied.

Data analysis

The statistical software PAST5 (version 5.22) was used to perform statistical analysis and generate visual representations of the data. Microplastic levels were assessed as the number of particles per particles per kilogram of compost material sample (particles/kg). Non-parametric statistical analysis, specifically the Kruskal-Wallis test for equal medians with Mann-Whitney pairwise post hoc comparisons, was employed to investigate and compare the occurrence of microplastics among different stages and seasons. Statistical significance was determined at a probability value (p-value) of 0.05. In addition, effect sizes (η^2) and 95% confidence intervals (CI) were reported to provide greater statistical robustness.

RESULTS AND DISCUSSION

Microplastics have been detected across multiple environmental compartments. Compost derived from organic waste should be free of various contaminants. Microplastics found in compost function as a channel for microplastics to permeate agricultural operations. This contributes to greater microplastic contamination in both land and agricultural products, including groundwater contamination. This stage-specific reduction pattern, accompanied by a shift from larger to smaller particles and changes in dominant polymers, provides novel insight into how composting influences microplastic fragmentation rather than simply transferring existing contamination. The current study underscores the essential factor of microplastic contamination in the composting process that utilizes municipal organic waste.

Abundance and occurrence of microplastic

In this study, 5042 microplastic particles were identified from a total of approximately (~)25 kg of samples from the composting process originating from landfills. Overall, the average abundance of microplastics was 201.53 ± 14.02 particles/kg. There was no significant difference ($p>0.05$) between microplastics identified from samples taken during the rainy season (202.61 ± 13.95 particles/kg) and the dry season (200.44 ± 14.09 particles/kg). The same microplastic abundance pattern was found in both sampling periods. Throughout the sampling process, the prevalence of microplastics appeared to diminish (Fig. 2A). The highest abundance was obtained from samples after the three-week fermentation period, while the lowest was obtained from samples of the compost product ready for sale (Fig. 3A and Fig. 3D). Microplastic contamination in compost products poses an additional challenge for managing microscopic plastic waste. Compost, frequently

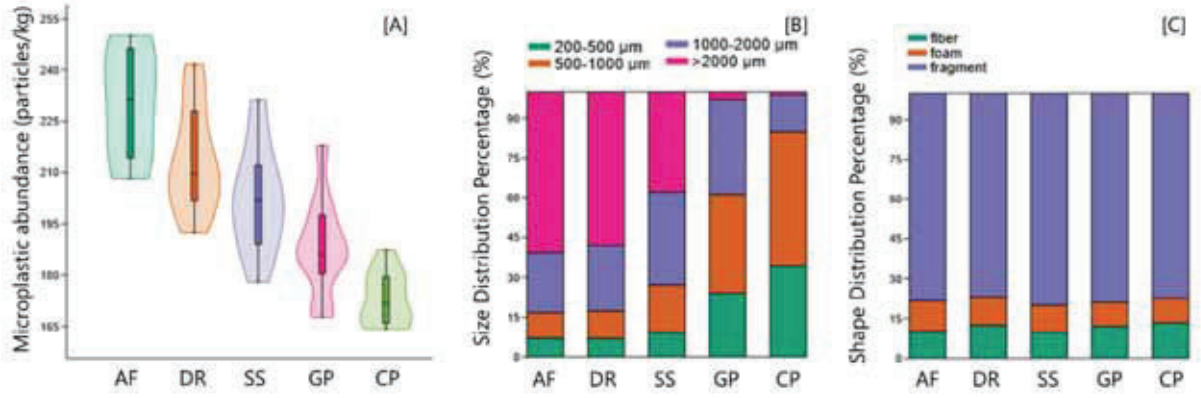

Fig. 2: Stage-specific microplastic abundance, size, and shape in the composting process. Panel A shows total microplastic abundance across composting stages; Panel B shows size distribution; Panel C shows shape distribution

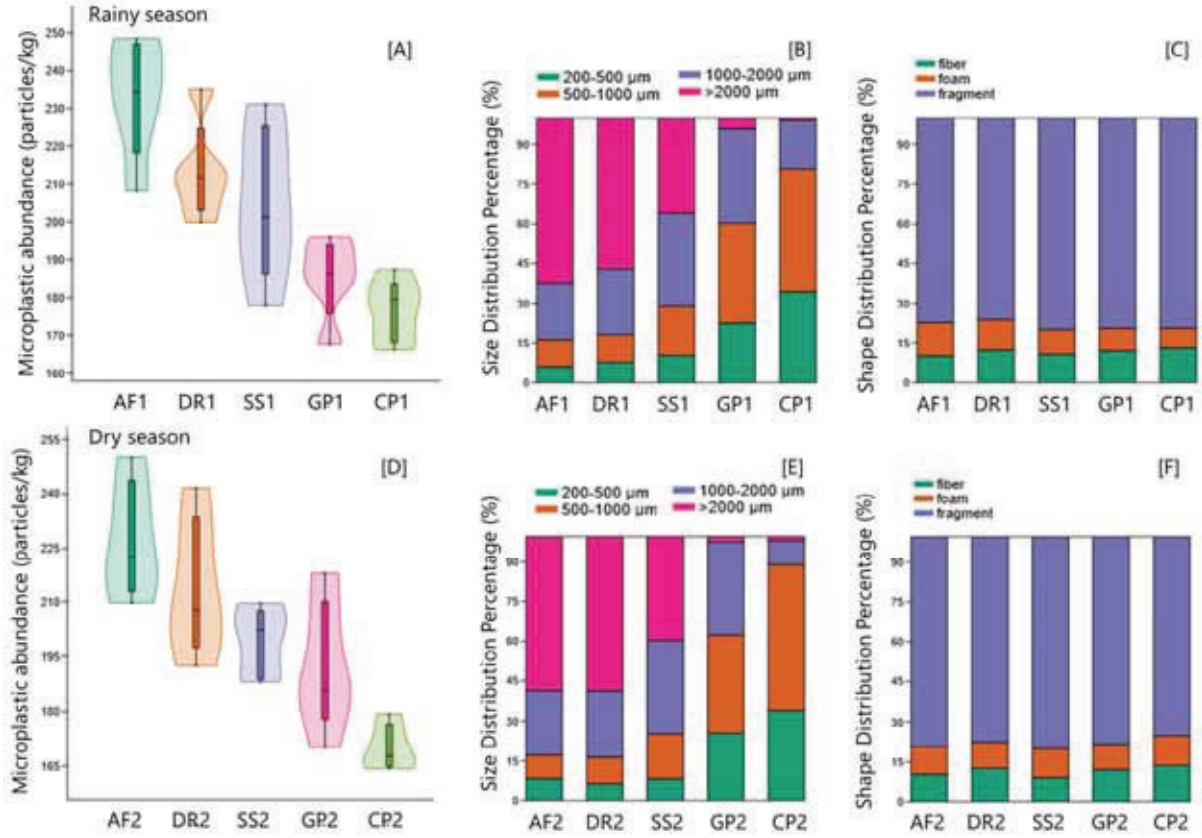

Fig. 3: Comparative seasonal patterns of microplastics across five composting stages. Panels A–C illustrate rainy season results for abundance [A], size [B], and shape [C]; Panels D–F illustrate dry season results for abundance [D], size [E], and shape [F]

utilized as both fertilizer and soil conditioner, is not exempt from microplastic contamination (Hölzle *et al.,* 2022). Contamination initiates when organic waste is combined with plastic waste, persists through each phase of the composting process, and finally results in the compost product ready for sale.

Waste management in Indonesia is similar to that in Global South countries, where waste is mixed between organic and inorganic waste (Abdulnabi Ali *et al.,* 2023; Omeyer *et al.,* 2022; Putri *et al.,* 2018). The absence of sorting exacerbates the situation, complicating the management of waste in landfills. In this study, Galuga Landfill has a composting facility, but plastic residues are still mixed with organic waste used for composting. This leads to plastic impurities being introduced into the composting process from the start until the finished product is prepared for sale. Most contamination originates from incoming mixed waste, particularly food packaging. Conversely, secondary inputs from shredders, grinding units, or conveyor belts may be significant. Future work should apply source differentiation protocols such as blank sampling of equipment surfaces. In general, Indonesia still practices open mixed waste disposal. However, despite the ban on open disposal being enacted since 2013, this practice continues (Meidiana *et al.,* 2022). The analysis indicates that more than 50% of the waste that reaches landfills is organic waste (Putra and Yuriandala, 2010; Suryani *et al.,* 2021). Waste should be sorted into at least organic and non-organic categories. However, since it remains mixed, particularly with plastic packaging, it indicates that compost generated in composting facilities often contains measurable amounts of microplastics. The findings of this study corroborate earlier research regarding compost products that include microplastics in both Iran and Switzerland (Berset and Stoll, 2024). However, this study's microplastic abundance is lower than that of those studies. Compost products from Iran ranged from over 16,000 to 1.8 million microplastic particles per kilogram (Alashti *et al.,* 2025). In Switzerland, reported microplastic concentrations in compost ranged between 195 and 1,315 particles per kilogram (Berset and Stoll, 2024). When assessing the situation in Indonesia against Iran (Alashti *et al*., 2025) and Switzerland (Berset and Stoll, 2024), the lower abundance in Indonesia may be attributed to the mixed composition of organic feedstock and a higher ratio of biodegradable organic matter. Methodological differences, including detection thresholds, also contribute to the observed variations. Moreover, the lower abundances observed in this study may partly reflect the current study detection threshold of 200 µm, which excluded smaller particles, and partly the dominance of organic fractions in Indonesian municipal waste, reducing the relative share of plastics compared to compost feedstock's in Iran and Switzerland (Berset and Stoll, 2024). The processes of fragmentation probably generate particles that are smaller than this threshold (for instance, nanoplastics). Small-sized particles abundance was not quantified here, but future work with higher-resolution techniques is necessary to assess nanoplastics presence.

A progressive decline in the abundance of microplastics was recorded from the three-week fermentation material to the final compost product intended for market. Statistical differences were particularly evident in samples subjected to three weeks of fermentation (AF) compared to ground products (GP) and ready-to-sell products (CP), with a p-value of <0.001, η^2 = 0.34, 95% CI: 0.22-0.46 (Fig. 2A). Significant statistical differences were also observed between AF and shredded products (SS), with a p-value of <0.05, η^2 = 0.11, 95% CI: 0.02-0.20. This pattern was consistent across different seasons and sampling periods. However, during the rainy season (Fig. 3A), significant differences were only noted between AF1 and GP1 as well as CP1 ($p<0.05$, η^2 = 0.15, 95% CI: 0.03–0.26). In contrast, during the dry season (Fig. 3D), microplastics abundance in CP2 was significantly different from all composting stages ($p<0.05$, η^2 = 0.19, 95% CI: 0.05–0.32), likely reflecting increased solar exposure. In the dry season, the increased temperatures and significant ultraviolet (UV) radiation result in the mechanical disintegration of plastics (Dimassi *et al.,* 2022). The consistent reduction pattern reflects combined mechanical (shredding, grinding), abiotic (UV and thermal exposure), and possible microbial contributions. These mechanisms collectively drive the decline from fermentation material to final compost. The decline in larger particles (>2000 µm) and the concurrent rise of smaller particles (200–1000 µm) indicates progressive fragmentation. The processes of shredding and grinding effectively lower particle size, while solar exposure compromises the tensile strength of polymers, facilitating the creation of smaller fragments. Monitoring should therefore include size-resolved analysis. In the Galuga Landfill, mixed waste is transported using open trucks and subsequently sorted manually into organic and inorganic waste (Nurhasanah *et al.,* 2021). Two processes are applied to the organic waste, allowing it

to be directly exposed to sunlight. Consequently, the plastic surfaces are exposed to solar radiation, which can elevate the plastic temperature beyond 50°C during the day (Rahman *et al.,* 2024). This exposure results in a reduction of tensile strength among polymers, leading to fragmentation under mechanical stress (Dimassi *et al.,* 2022). The fragmentation process integrates macro-sized plastics into the initial stages of compost production, and during the dry season, the fragmentation rate escalates due to higher levels of UV radiation (Dimassi *et al.,* 2022; Rahman *et al.,* 2024). The decrease in particle size observed aligns with shredding, grinding, and solar exposure, yet this interpretation is still based on inferential. Future work involving controlled UV degradation and mechanical stress tests is needed to confirm the specific fragmentation mechanisms.

Characteristics of microplastic

A notable pattern was found based on further analysis of microplastics' size (Fig. 2B, Fig. 3B and Fig 3E) and shape characteristics (Fig. 2C, Fig. 3C and Fig 3F). Large microplastics (>2000 µm) tended to decrease from the early stage (60.61% proportion) to the finished product (1.27%), while smaller microplastics (between 200-1000 µm) increased from the initial stage of compost production (7.13%) to the final stage of finished compost (34.22%). The identical pattern of microplastic size ratios was noted in samples collected during both seasons. The overall pattern of reduction was similar in rainy and dry seasons because composting procedures were identical. Nevertheless, heightened UV exposure throughout the dry season expedited fragmentation, leading to reduced particle sizes, despite total abundance stayed relatively similar. The most common microplastic shape was fragments (75.12-79.92%), followed by fibers (9.04-13.62%). Foam was the least common microplastic shape, with a proportion of 7.47-11.57%. Fragments were the most common microplastic shape because these fragments originated from organic waste and mixed waste packaging. Before the three-week fermentation process, macro-sized plastic (>2.5 cm) was still present. This resulted in plastic mixing with organic waste, the primary material for compost production. After the fermentation process and two days of drying, the large plastic pieces broke down into smaller, fragmented pieces. These microplastics typically share similar shapes and sizes, with the fragments reducing in size and their proportion elevating in the final compost product. Microplastics in compost products are found in various sizes and shapes. The characteristics of these microplastics were shaped by the nature of organic waste processed, the specific composting practices carried out, and the characteristics of the plastic mixed in the raw material. The results of studies related to the characteristics of microplastics in compost align with previous research (Alashti *et al.,* 2025; Berset and Stoll, 2024). The size of microplastics in compost products generally ranges from 100 to 1000 µm (Iswahyudi *et al.,* 2024; Liu *et al.,* 2025). These sizes can be relatively visible to the naked eye or exceptionally small. The smaller the size, the more difficult it is to detect, remove, and the more likely it is to contaminate agricultural products that use compost products (Liu *et al.,* 2025; Sholokhova *et al.,* 2023). The gradual decrease in microplastics' size over time signifies shifts in the physicochemical properties of plastic at that scale. Fermentation, drying, shredding, and grinding processes accelerate the anaerobic and mechanical fragmentation of plastic (Sholokhova *et al.,* 2023). This results in a correlation between the plastic found in raw waste, which is the source of compost products, and microplastics in the compost source (Liu *et al.,* 2025). A study carried out in Iran revealed that fiber-shaped microplastics made up approximately 75% of the microplastics present in compost products (Alashti *et al.,* 2025). Similar results were found in another study on microplastics in compost products in Indonesia (Iswahyudi *et al.,* 2024), with fragment-shaped microplastics dominating (>80%). Both studies demonstrate that the characteristics of the raw waste utilized as the source for compost products were directly associated to the varieties of microplastics later found in the end products (Alashti *et al.,* 2025; Iswahyudi *et al.,* 2024).

The identification of microplastics recovered in this study was further enhanced by analyzing the chemical composition of the particles. Eight types of polymer groups were identified. Analyzing 1,068 particles from a total of 5,042 revealed that polyethylene, polypropylene, and polystyrene were dominant, together representing 72.10% of the identified polymers. Other identified polymers included polyethylene terephthalate, polyester, polyvinyl chloride, alkyd resin, and nylon (Table 1). Global studies on the chemical composition of

Table 1: Identified polymer types for all samples and different sampling seasons

Polymer type	Total sample		Rainy season		Dry season	
	Count	%	Count	%	Count	%
Polyethylene	383	35.86	200	38.02	183	33.76
Polypropylene	252	23.60	118	22.43	134	24.72
Polystyrene	135	12.64	73	13.88	62	11.44
Polyethylene terephthalate	103	9.64	42	7.98	61	11.25
Polyester	65	6.09	33	6.27	32	5.90
Poly vinyl chloride	68	6.37	32	6.08	36	6.64
Alkyd resin	36	3.37	12	2.28	24	4.43
Nylon (6,9)	26	2.43	16	3.04	10	1.85
Total	1068	100	526	100	542	100

compost and fertilizer products have been carried out, often producing results that align with those of this study, where polypropylene and polyethylene are commonly detected (Liu *et al.,* 2025; Ruffell *et al.,* 2025). The predominance of polyethylene, polypropylene, and polystyrene is linked to the use in packaging. Polyethylene and polypropylene, with lower densities and higher crystallinity, are prone to fragmentation under thermal and mechanical stress, while polystyrene tends to form smaller brittle fragments due to its aromatic backbone. The significant presence of polyethylene, polypropylene, and polystyrene showcases their dominance in the packaging of food and beverages in municipal waste. The resilience and chemical stability of these polymers facilitate their survival during composting, underscoring the necessity for upstream waste sorting and packaging strategies. This similarity suggests that the raw materials for compost largely comprise food and beverage packaging waste, plastic bags, and single-use plastic products entering the composting process (He *et al.,* 2019; Steiner *et al.,* 2024). Although FTIR analysis in this study identified polymer composition without direct surface characterization, previous research indicates that composting conditions promote oxidation, surface cracking, and potential additive leaching. These modifications could impact the quality of compost and require additional examination. In Indonesia, particularly at the Galuga landfill, these plastics are also prevalent in leachate water (Nurhasanah *et al.,* 2021). The observed polymer-specific changes, along with a consistent reduction pattern across composting stages, demonstrate novelty beyond previous compost studies (Berset and Stoll, 2024; Porterfield *et al.,* 2023; Sholokhova *et al.,* 2023; Weithmann *et al.,* 2018). Different types of plastics highlight the significant difficulties encountered in managing plastic waste within Indonesian landfills, particularly at composting facilities.

Environmental implications, mitigation and future research directions

This study demonstrates the presence and stage-specific reduction of microplastics during composting. Broader implications such as soil health, microbial interactions, and potential carbon sequestration effects are highlighted here as contextual risks, based on previous studies (2025; Berset and Stoll, 2024; Porterfield *et al.,* 2023; Sholokhova *et al.,* 2023; Weithmann *et al.,* 2018), rather than direct outcomes of the current dataset. Organic waste that is processed into compost can function as an effective fertilizer, enriching soil conditions for agricultural fields (Tiwari *et al.,* 2023). Currently, there is a global trend towards increased consumption of natural fertilizers in gardening and agriculture, aimed at improving soil health and reducing reliance on chemical inputs (Tiwari *et al.,* 2023). Compost derived from municipal waste is more susceptible to having contaminants, like microplastics, than compost produced from green waste (Berset and Stoll, 2024). Furthermore, the composting process itself may generate microplastics (Sholokhova *et al.,* 2023). The introduction of compost contaminated with microplastics has the potential to alter soil amendment and disrupt microbial communities (Zhang *et al.,* 2024). Additional risks include bioaccumulation, biomagnification, and the dispersal of microplastics into surrounding environments and groundwater (Wahl *et al.,* 2024). Once compost is applied, residual microplastics may persist in soil for

decades, migrate through soil pores, or be taken up indirectly through soil, plant, and microbe interactions. These pathways emphasize the potential risks to agricultural systems and validate the necessity for additional risk assessment studies. Microplastics remaining in compost can leach downward into groundwater during rainfall or irrigation events, while smaller fragments and fibers may be dispersed by wind erosion. The focus of mitigation should be on reducing sources and improving the screening quality of compost before it is applied to land. Some evidence suggests microplastics can persist in soils for several decades, raising concerns for long-term soil health and productivity (Moeck *et al.,* 2023; Salama and Geyer, 2023; Wahl *et al.,* 2024). While this study did not measure chemical leachates like phthalates and bisphenols, earlier study suggests that these substances may be released during the composting process. This may present human and ecological risks, underscoring the need for future chemical monitoring of compost leachates. The binding of chemical additives to humic substances and organic fractions in compost can lead to their long-term presence and buildup. This interaction could affect compost quality and poses risks for agricultural application, warranting further assessment against safety standards. The presence of residual microplastics can lead to a decrease in microbial diversity, modify nutrient cycling, and in some situations, limit the production of plant biomass. Laboratory studies indicate that uptake of microplastics and chemicals associated by crops may occur, with potential impacts on food quality and agricultural productivity (Moeck *et al.,* 2023; Salama and Geyer, 2023). Field-scale measurements cannot fully separate the role of composting parameters such as aeration, temperature, moisture, or duration in microplastic reduction. Future controlled pilot experiments are vital for refining these parameters and verifying the stage-specific trends that have been observed. This study examines the potential pathway of microplastics during the composting process. While previous research has confirmed microplastic presence in commercial compost products, the study findings indicate a reduction in microplastic concentrations across the five composting stages, indicating a viable opportunity for mitigating microplastic contamination in the final product intended for sale. The preliminary phase, prior to fermentation, presents a vital chance for early manual pre-sorting (Zhang *et al.,* 2022). Ideally, source segregation of raw materials should be implemented (Cordova, 2024). However, in Indonesia, this system is currently weak due to mixing domestic waste, leading to plastic fragmentation. Substantial reductions in contamination risks could be achieved through the early pre-sorting of compost feedstock and the regulatory reduction of plastic packaging. Implementation in Indonesia faces challenges in waste segregation compliance, but gradual enforcement and incentives for plastic alternatives are promising strategies. Throughout the first composting stage (the fermentation process), the biodegradation of plastics can be facilitated by microorganisms such as bacteria or fungi, which can help eliminate microplastics and promote effective compost production (Tiwari *et al.,* 2024). Microbial colonization of microplastics during composting is possible, as previous studies (Moeck *et al.,* 2023; Salama and Geyer, 2023) show bacterial and fungal enzymes capable of degrading polymers such as polyethylene and polyethylene terephthalate. Composting factors greatly affect microbial activity. Under thermophilic conditions, the potential for enzymatic degradation of certain polymers is increased, while mesophilic phases allow for extended microbial colonization. Variability in moisture and pH also affect fragmentation pathways and warrant further controlled testing. While not directly assessed here, this process could contribute to the observed fragmentation and requires targeted microbial analyses in future work. Transitioning composting methods to prolong thermophilic stages may boost microbial activity and facilitate polymer breakdown, whereas mesophilic stages aid in sustained degradation. However, engineering changes must consider energy demand and operational costs to remain practical for municipal facilities. In the next stage, manual sorting is the practical approach for handling mixed waste in composting facilities. Furthermore, operators can invest cost-effective separation technologies such as water flotation and airflow separators (Bauer *et al.,* 2018; Stessel and Peirce, 1985). These mechanisms segregate materials by density, allowing plastics to either float or be removed by air flow, while organic waste sinks or is kept in place (Bauer *et al.,* 2018; Stessel and Peirce, 1985). These technologies are

relatively low-cost but require evaluation for scalability and potential environmental side effects. These methods may pose water and air quality risks, requiring attention. The following step to decrease microplastic contamination entails implementing extra physical removal techniques while shredding and sieving, which demands dual or triple operations for optimal results. During the grinding phase, care must be taken to minimize contamination from larger plastic fragments, preventing them from being broken down into smaller pieces. Although mechanical shredding and solar exposure evidently contribute to fragmentation, microbial metabolism might additionally compromise polymer structure via oxidative enzymes. This dual mechanism may explain the observed size reduction; though controlled experiments are needed to distinguish biological from physical contributions. By examining both the short- and long-term effects of microplastics on agricultural land, as well as the potential pathways involved in the composting process and possible mitigation measures, there is an evident need for research guidelines that could be integrated into existing regulations Residual microplastics in compost pose long-term risks for soil health, groundwater contamination, and food safety. These results necessitate more robust agricultural guidelines, tighter regulations on compost quality, and the incorporation of microplastic thresholds into national standards to improve sustainability. At present, no globally accepted threshold for microplastic content in compost is established. Some European initiatives propose preliminary limits, but the current results suggest final compost in Indonesia still contains measurable contamination. This emphasizes the necessity for unified standards to guarantee safe agricultural practices. Future studies should address the gaps in the technical processes to reduce microplastics during compost production. An improved method can be created to lessen microplastic contamination by focusing on these shortcomings. Additionally, it is crucial to assess the potential for microplastics to leach from compost-amended soils. Further investigations are needed to fully comprehend the consequences of microplastic contamination for both soils and crops, particularly regarding the effects on soil organisms and plant health. On the other hand, given the dual challenge of climate change, it is vital to investigate how microplastics from compost products derived from municipal waste affect carbon sequestration. From a regulatory viewpoint, there is a critical necessity for enhanced regulations to address microplastic contamination in compost products, which could aid in alleviating environmental impacts. Moreover, adopting natural-based plastics and reducing single-use plastics could significantly lower soil microplastic contamination through municipal waste-based compost products.

CONCLUSION

This comprehensive study elucidates the stage-specific variations in microplastic abundance and polymer composition during the composting process. It emphasizes the dynamics of process-based reduction and fragmentation, presenting new insights from Indonesia's composting systems. This study delivers new information on the progressive variations in microplastic presence and polymer composition as composting occurs. Notably, the abundance of microplastics exhibited a consistent decline, transitioning from the three-week fermentation product to the final compost output. Remarkable reductions in microplastic content were particularly evident following the shredding and grinding stages, highlighting the significance of mechanical breakdown in reducing the presence of plastics. Across the multiple stages of composting, microplastic fragments emerged as the leading form. However, as the larger plastic particles underwent degradation, there was a noticeable increase in the relative proportion of smaller particles. The analysis of polymer composition revealed a diverse array, with polyethylene, polypropylene, and polystyrene emerging as the most prevalent types. This pattern vividly demonstrates the considerable influence of single-use plastics within the organic waste stream, notably including items like plastic bags and food packaging. The findings also underscore the potential of composting to markedly diminish plastic contamination levels. However, this research also highlights an unforeseen consequence. There is an increase in the risk of microplastic contamination in compost derived from municipal waste. To overcome this issue, a forward-thinking strategy is required, which encompasses enhanced sorting at the origin and pre-sorting strategies that incorporate biotechnological advancements within composting

operations. Throughout the first composting stage (the fermentation process), the biodegradation of plastics can be facilitated by microorganisms such as bacteria or fungi, which can help eliminate microplastics and promote effective compost production. In the subsequent phase, manual sorting serves as the effective method for managing mixed waste in composting facilities. Furthermore, operators can invest in separation technologies such as water flotation and airflow separators. From a regulatory perspective, there is an urgent need for stricter regulations to address microplastic contamination in compost products, which could help mitigate environmental impacts. Embracing bioplastics and minimizing the use of single-use plastics could greatly reduce soil microplastic pollution stemming from compost products derived from municipal waste. The implications of this study underscore composting's promise as a means of environmental mitigation while simultaneously calling for urgent improvements in upstream waste separation strategies. Such enhancements are crucial for minimizing plastic inputs, ultimately safeguarding land and agricultural products from the pervasive threat of microplastics.

AUTHOR CONTRIBUTIONS

Nurhasanah contributed to the conceptualization, formal analysis, result interpretation, and manuscript preparation, including both original drafting and subsequent revisions. Hasrianti was involved in the interpretation of results and assisted in the preparation and critical review of the manuscript. L. Hakim participated in the interpretation of findings and contributed to the manuscript review and editing process. E. Riani was responsible for designing the field sampling, conducting data curation, performing formal analysis, and contributing to the interpretation of results, and manuscript revisions. M.R. Cordova served as the principal contributor, with primary responsibility for conceptualization, supervision, study design, laboratory investigations, data analysis, and manuscript writing, and manuscript revisions.

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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.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

~	approximately
η^2	effect sizes
%	percent
µm	Micrometer or micron
°C	degree Celsius
/cm	A reciprocal centimeter (or wavenumber)
AF	Compost processing samples after the three-week fermentation period
ATR-FTIR	Attenuated Total Reflectance - Fourier Transform Infrared Spectroscopy
cm	Centimeter
CI	confidence intervals
CP	the compost product that is ready for sale
DR	the two-day drying of the fermented compost processing product
$Fe(II)SO_4$	Iron(II) sulfate or ferrous sulfate
FLOPP	FTIR library of plastic particles
g	gram
GP	the grinding process for compost processing product
h	hours
Ha	Hectare
H_2O_2	Hydrogen peroxide
kg	Kilogram
mg/mL	milligrams per milliliter
mL	milliliter
particles/kg	Particles per kilogram
p-value	probability value
SS	the shredding stage for compost processing product
UV	ultraviolet
$ZnCl_2$	Zinc chloride

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CASE STUDY

Diagnostic multidimensional scaling of institutional and environmental sustainability in a regional public rice enterprise

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ABSTRACT

BACKGROUND AND OBJECTIVES: In developing countries, regional public enterprises are progressively anticipated to serve as catalysts for environmental sustainability within agricultural systems. The study objectives were to apply a multidimensional scaling framework to evaluate the sustainability performance of a regional enterprise in Indonesia across five interconnected dimensions: environmental-agricultural, agrotechnology, institutional, business opportunity, and social.

METHODS: A mixed-methods framework integrated primary data collected through structured interviews involving farmers, business owners, and stakeholders, alongside secondary data derived from literature and government reports. The multidimensional Scaling method, implemented using the Rapid Appraisal for Fisheries program, was employed to examine 38 attributes spanning five dimensions of sustainability. To validate the results and confirm data reliability, a Monte Carlo analysis was carried out

FINDINGS: The calculated sustainability index for rice farming indicates moderate sustainability in regional public enterprises. The overall sustainability index was 46.60 percent. This score represents a status that is categorized as less sustainable based on the defined classification (25.01 to 50 percent represent less sustainable). It highlights fragmented sustainability efforts across environmental (46.31 percent), technological (50.07 percent), institutional (43.91 percent), business (48.37 percent), and social (44.34 percent) dimensions. Key leverage factors identified were the adoption of environmentally friendly technology (4.92 percent), production and marketing capacity (2.87 percent), water use efficiency (2.93 percent), staff well-being (1.20 percent), and enterprise risk management (1.40 percent). These observations demonstrate the mutual dependence of environmental and non-environmental components in securing sustainability. Despite existing environmental efforts, implementation remains fragmented due to insufficient infrastructure, low awareness, and weak institutional commitment.

CONCLUSION: A multidimensional scaling method was used to assess sustainability performance in the regional agriculture sector. Considerable shortcomings were detected in environmental performance, institutional integration, and technology readiness. Addressing these gaps requires coordinated governance, infrastructure investment, and strategic alignment with sustainability objectives. These results provide analytical insights for evaluating sustainability in public enterprises and serve as practical guidance for harmonizing institutional performance with environmental stewardship. The results support progress toward Sustainable Development Goals 2 (Zero Hunger) and 13 (Climate Action) by emphasizing the value of integrated assessment approaches for guiding the transition toward low-carbon agricultural practices. Proposed policies emphasize the importance of investing in post-harvest technology, enhanced digital marketing and rural infrastructure, stronger farmer organizations, improved risk management, and sustainable environmental practices. Encouraging reforms in governance, inter-sector collaboration, and of policies is vital for facilitating systemic transformation.

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INTRODUCTION

The sustainability of agricultural systems, particularly rice production has become a strategic issue in global development agendas (Shi *et al.,* 2023). This sense of urgency stems from critical issues including climate change, land degradation, and risks to food security (Li *et al.,* 2024). Rice is a key dietary component for over fifty percent of the world's population, however, its production significantly impacts greenhouse gas emissions and leads to water shortages (Gao *et al.*, 2025). Rice production plays a critical role in ensuring food security and economic stability for many developing countries. It supports rural employment and functions as a strategic commodity. Nonetheless, its effect on the climate and ecology jeopardizes long-term sustainability (FAO, 2021). Sustainable rice cultivation is essential to achieve the sustainable development goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action) (FAO, 2021). These global goals stress the importance of changing agricultural systems to boost productivity while safeguarding environmental integrity. In alignment with these priorities, Indonesia has prioritized food sovereignty and sustainability through Law No. 18/2012 on Food and Law No. 22/2019 on Sustainable Agricultural Systems. Regional agricultural enterprises (RAEs) have the responsibility to carry out this vision through the management of agri-food infrastructure, the enhancement of market efficiency, and the upliftment of farmer welfare (Akuriba, 2021). Sukabumi Regency, in West Java Province, has significant agroecological potential in agriculture, livestock, marine, and fisheries sectors. This potential positions Sukabumi as a key driver of regional food security and resilience (Purba, *et al.,* 2024). According to the Statistics Indonesia, (2023), the region produced 181,282 tons of milled dry rice, with an average yield of 5.3 tons per hectare, exceeding the national average. Its strategic role supports Indonesia's 2045 food sovereignty agenda, particularly in optimizing regional superior commodities (Khumairoh, *et al.*, 2024). This vision is consistent with SDG 2, as underscored by the 2023 State of Food Security and Nutrition report, which estimated that 733 million individuals worldwide experienced chronic hunger (Arora and Mishra, 2025). Financial mechanisms in sustainability transitions are increasingly recognized as a core enabler of agricultural transformation. Access to affordable credit, green financing schemes, and result-based subsidies accelerate the adoption of sustainable practices among smallholder farmers (Piñeiro *et al.,* 2020). Conversely, funding deficiencies, including delayed capital disbursement or a lack of adequate working capital, can impede the execution of climate-smart technologies (De Pascale and Guadagno, 2025). Tailored financial incentives aligned with environmental performance can improve productivity and ecological outcomes simultaneously (Nguyen *et al.*, 2024). Despite this potential, the sustainability of Sukabumi's rice system has not been comprehensively assessed across key dimensions: economic, social, environmental, technological, and institutional. Due to its agroecological benefits and its importance to Indonesia's food security initiatives, Sukabumi serves as an vital location for the advancement of sustainable agricultural frameworks (Rachman *et al.*, 2022). Sukabumi also exemplifies the complex challenges facing regional agricultural systems. Although historically a major rice-producing area, it now faces escalating environmental threats, including water scarcity, declining soil fertility, and increasing climate variability (Mali *et al.*, 2023). Besides ecological challenges, the area is hindered by restricted access to markets and insufficient infrastructure for post-harvest processing (Cahyono and Indrayani, 2020). Farmers also face weak bargaining power in the value chain (Purwandoko *et al.*, 2024). In response, the district government established Perumda Agro Sukabumi Mandiri through Regional Regulation No. 2/2020. The organization was assigned the responsibility to stabilize rice prices, upgrade post-harvest systems, and promote rural development. However, it faces significant structural constraints, such as financial limitations and institutional ambiguity (Syahza *et al.,* 2024). Without instruments like crop insurance or stabilization funds, the enterprise remains exposed to market and climate risks. Grasping how farmers and communities view and react to sustainability initiatives is essential for successful transitions in agri-food industry (Markiewicz-Keszycka *et al.,* 2025). Behavioral responses are shaped by economic logic, local values, and access to extension services (Whitton and Carmichael, 2024). In Indonesia, access to knowledge and profit orientation are key motivators (Santoso, *et al.*, 2023). Farmers often equate sustainability with income and resilience rather than solely

environmental protection (Baccar *et al.,* 2020). Obstacles consist of intricate regulations, insufficient incentives, and skepticism towards government initiatives (Gemtou *et al.,* 2024). Long-term sustainability performance is most effectively measured through time-series analysis, capturing productivity trends, input efficiency, and input–output dynamics. In Indonesia, such initiatives continue to be restricted because of fragmented data systems. To address this, the present study establishes a local sustainability baseline using multidimensional Scaling (MDS), with AI-based forecasting and remote sensing support (Tai *et al.,* 2023). National and regional policy frameworks are central to shaping sustainable outcomes. In Southeast Asia, progress is constrained by fragmented mandates and regulatory overlap (Iqbal *et al.,* 2022). Organizations such as Perumda Agro require well-defined policies to effectively achieve their objectives. Scalability and replicability are crucial for expanding effective sustainability models. The approach used by Perumda Agro integrating post-harvest management, price stabilization, and partnerships offers potential for other regions with similar agroecological settings (Thierfelder and Mhlanga, 2022). Nonetheless, the ability to transfer is contingent upon infrastructure, financial accessibility, and the robustness of institutions. In spite of the presence of numerous local agricultural initiatives, there is a notable absence of quantifiable data and integrative evaluations to assess the sustainability of rice production in Sukabumi. Most studies to date focus on isolated issues such as price stabilization, ecological degradation, or infrastructure gaps without addressing the interplay across dimensions (Ngongo *et al.*, 2021). The disparity between technical policy and on-the-ground realities obstructs evidence-based decision-making, particularly in regions experiencing institutional fragmentation and environmental pressures (Akuriba, 2021). This study aims to assess the sustainability performance of the rice production system in Sukabumi Regency using a quantitative diagnostic approach based on MDS. This technique facilitates the transformation of professional evaluations into quantifiable sustainability metrics and visual interpretations. Data were collected through focus group discussions and structured questionnaires built around the rice value chain. Five key dimensions (economic, social, environmental, technological, and institutional) were assessed using a Likert scale, then analyzed through the RAPFISH application. MDS was chosen for its proficiency in dealing with complex systems that have restricted statistical data, making it ideal for shaping policy and strategic initiatives (Salassa *et al.,* 2025). MDS has been widely applied to evaluate sustainability in agricultural systems. Previous studies include assessments of algal biomass (Santoso *et al.,* 2023a), duck farming (Bakrie *et al.,* 2023), dairy production (Lovarelli *et al.*, 2020), rice cultivation (Rachman *et al.*, 2022), cattle farming (Rohaeni *et al.*, 2024), animal feed from sago (Allaily *et al.,* 2024), waste management (Ismail *et al.,* 2025), composting (Santoso *et al.*, 2024b), and integrated farming systems (Widjaja *et al.*, 2024). Nevertheless, there are limited studies that have utilized MDS to evaluate the sustainability of regional agricultural businesses including Perumda Agro Sukabumi Mandiri, especially with a cross-dimensional focus. This study introduces both conceptual and methodological novelties. First, it offers a cross-dimensional evaluation of rice sustainability using five integrated dimensions. Second, it emphasizes a regional agricultural business as the focal point of analysis, delivering insights into institutional roles in sustainability transitions. Third, MDS applies to the context of rice systems, where such comprehensive approaches are rarely used. In combination, these factors bridge essential gaps in empirical studies and provide a novel structure for localized sustainability evaluations. The evaluation results are expected to not only measure the sustainability status of rice farming in Sukabumi but also to identify key enabling and constraining factors in each dimension. These findings can inform policy priorities for local governments, agricultural businesses, and farmer organizations. The study aids in the progress of climate-smart agriculture, evidence-based investment strategies, and performance-based incentives through the provision of empirical benchmarks and visual diagnostics. This study has strategic value for planning sustainable agricultural development in Sukabumi. It aims to align the interests of farmers, market actors, technical agencies, and policymakers across executive and legislative bodies. The findings support improvements in governance, investment, and circular practices within decentralized food systems, aligning with national goals and SDG Targets 2.3, 2.4, and 13.2

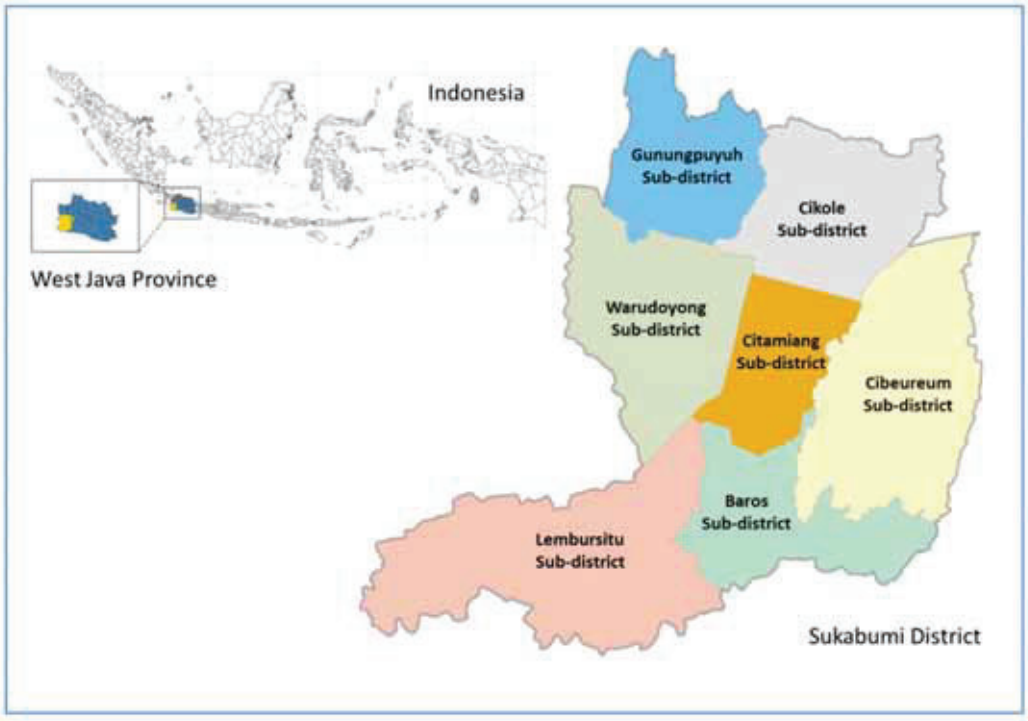

Fig. 1: Geographical location of the study area in Sukabumi of West Java Province in Indonesia

(FAO, 2021). The study was conducted by the research group on Optimization of Production Systems at the National Research and Innovation Agency (BRIN), Indonesia, during the period 2024 to 2025.

MATERIALS AND METHODS

Characteristics and potential of Sukabumi

Sukabumi is located in West Java Province, Indonesia (Fig. 1). Administratively, Sukabumi City consists of 7 subdistricts and 33 villages. The land area of each subdistrict follows as; Citamiang with 4.01 square kilometers (km^2), Gunungpuyuh (5.15 km^2), Baros (5.58 km^2), Cikole (6.22 km^2), Lembursitu (10.69 km^2), Cibeureum (9.12 km^2), and Warudoyong (7.56 km^2).

Sukabumi City has development potential despite its relatively small size. The combination of field observations and imaging data analysis points to rice fields and mixed gardens as the leading land use in Sukabumi City for the year 2018. Urban residential, commercial, industrial, and office buildings also occupy significant areas. Urban residential buildings represent the largest land use, covering 1,736.63 hectares (ha), or 35.73 percent (%) of the total land area. The area used for rice fields is 1,661.03 ha (34.37% of the total area). Approximately 340.66 ha, or 7.05% of the land, comprises office, commercial, and industrial structures. In the northern part of Sukabumi, particularly in the valleys of Mount Gede Pangrango, irrigation systems are standard due to abundant river water supply. Moving away from the highlands results in increasingly limited access to water, which forces many farmers to depend on rainfed systems that are heavily reliant on seasonal rainfall. Due to the growing tourism industry, land conversion is one of the most significant issues farmers face, particularly in the Ciletuh Geopark area in the Ciemas District. A study by Akliyah *et. al*, (2023) found that many paddy fields in this region have been transformed into villas, lodgings, and other tourism facilities, threatening the sustainability of rice farming. The Sukabumi Regional Government has started to promote agrotourism as a strategic option to mitigate the negative impact of tourism growth. This strategy empowers the tourism industry to draw in more visitors while simultaneously improving agricultural sustainability by integrating farmland into tourist attractions. Consequently, farmers can

maintain primary livelihoods while deriving additional economic benefits from tourism activities.

Research material and procedure

This study examined the management of rice farming using a mixed-methods approach. Data pertaining to agricultural sustainability, especially in rice production, was collected from academic articles and pertinent policy documents. Direct observations and structured interviews were conducted with farmers, business owners, and stakeholders to enrich the primary dataset. A total of seven respondents were purposively selected, including representatives from farmer cooperatives, agro-enterprise managers, local government officials, and agricultural extension officers. The criteria for selection included involvement with institutions, sustainability proficiency, and active contribution to the regional rice value chain. Additional insights were obtained through interviews with agricultural researchers and farmer community professionals. The collected data were analyzed using the MDS method, supported by the Rapid Appraisal for Fisheries (Rapfish) program (Rachman *et al.*, 2022). The study assessed 38 attributes across five sustainability dimensions: business opportunity, institutional, social, agro-technological, and environmental-agricultural. The operationalization of these attributes followed a structured, multiphase process. A preliminary set of indicators was established through an examination of existing literature and national agri-environmental policy frameworks. The refinement of these indicators was accomplished through two rounds of expert consultation using a modified Delphi technique, where consensus was established when 75% or more of the participants recognized the indicator's relevance. The final attributes were categorized into five sustainability dimensions, ensuring both diagnostic precision and policy relevance. Nguyen *et al.* (2024) emphasize the importance of adapting sustainability frameworks to smallholder agricultural contexts. Separately, Panpakdee *et al.* (2022) highlight the necessity of embedding validated indicators within rural development strategies to promote effective sustainability transitions.

Sustainability analysis of rice production

In MDS, the arrangement of objects within a dimensional space is executed in a manner that the distances among them indicate their level of similarity. The more similar two objects are, the closer they appear in the resulting spatial configuration. Deng *et al.* (2024) studies, the MDS technique commonly applies Euclidean distance in n-dimensional space to determine these relationships, using Eq. 1 (Chrispin *et al.*, 2022):

$$d = \sqrt{((x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2 + \dots)} \quad (1)$$

In this context, the spatial arrangement of points is achieved by regressing the Euclidean distance (d_{ij}) between point i and point j, based on a reference point or origin (o_j). This relationship is modeled using a linear regression, using Eq. 2 (Chrispin *et al.*, 2022):

$$\hat{d}_{ij} = \alpha + \beta\delta_{ij} + \varepsilon \quad (2)$$

Where;

$\hat{d}_{ij}$ is the estimated Euclidean distance, δ_{ij} is the observed dissimilarity between points i and j, α and β are regression parameters, ε is the residual error

The ALSCAL (Alternating Least Squares Scaling) algorithm is typically used to minimize the discrepancy between observed and estimated distances. It works by optimizing the squared differences between input dissimilarities and Euclidean distances, known as S-Stress, using Eq. 3 (Chrispin *et al.*, 2022):

$$s = (1/m) \sum_{k=1}^{m} [\sum_{i<j} (\hat{d}_{ijk}^2 - \delta_{ijk}^2)^2 / \sum_{i<j} \delta_{ijk}^4] \quad (3)$$

Where;

s is the S-Stress value, m is the number of replications or dimensions, $\hat{d}_{ijk}$ is the estimated squared Euclidean distance between points i and j in condition k, δ_{ijk} is the corresponding dissimilarity

Finally, the squared Euclidean distance used in these computations is defined by Eq. 4 (Chrispin *et al.*, 2022):

$$\hat{d}_{ijk} = \sum_{n=1}^{r} w_{ka} (x_{ia} - x_{ja})^2 \quad (4)$$

Where;

w_{ka} represents the weight assigned to dimension a in replication k,

x_{ia} and x_{ja} are the coordinates of points i and j along

dimension a,

r is the number of dimensions considered

Sustainability performance in rice farming is categorized into four levels, with benchmarks at 100%, 75%, 50%, 25%, and 0%. Score ranges define the sustainability assessment categories. Scores of 75.01–100.00 indicate a sound and sustainable condition; 50.01–75.00, a fairly sustainable level; 25.01–50.00, less sustainable status; and 0.00–25.00, an unsustainable and inadequate state. Leverage analysis determines the most significant factors based on their root mean square (RMS) scores, identifying sensitive sustainability indicators. Leverage factors that fall below 2% are trivial, while those that go beyond 8% are regarded as critical and fundamental to sustainability. The leverage values range from 2% to 8%, indicating a moderate to strong influence (Rachman *et al.,* 2022). The primary and significant factors are detailed in Table 1.

In evaluating sustainability within complex agri-food systems, the MDS technique offers a versatile and integrative framework. One significant advantage is its capacity to convert expert knowledge into measurable sustainability scores without the need for extensive datasets or strict statistical models (Zare, *et al.,* 2021). MDS is particularly valuable for identifying the most influential attributes, known as leverage factors. This helps institutions like Perumda Agro Sukabumi Mandiri focus on strategic priorities instead of treating each indicator in isolation. Furthermore, MDS generates user-friendly graphical representations that aid in visualizing intricate multidimensional relationships, thereby improving stakeholder comprehension (Sittadewi, *et al.,* 2025). This method is valued in sustainability assessments for balancing analytical rigor with participatory approaches, making it suitable for regions with limited data or institutional resources (Da Silva *et al.*, 2023). Consequently, the implementation of MDS in this study promotes an all-encompassing and realistic appraisal of sustainability across various dimensions, including environmental, technological, institutional, economic, and social aspects. Monte Carlo analysis helps determine errors and assess uncertainty in MDS. When MDS and Monte Carlo values differ only slightly, a 95% confidence level indicates that the sustainability assessment is reliable.

RESULTS AND DISCUSSION

Key attributes in rice production

Determining the sustainability index involves methodically recognizing characteristics within every dimension through scientific evaluation. Specificity and consideration of temporal aspects are essential for attribute classification (Rendrarpoetri *et al.,* 2024). This study identified 38 attributes spanning environmental-agricultural, business opportunity, social, agrotechnology, and institutional dimensions Table 2.

Index of sustainability

Researchers interpreted every aspect of sustainability dimension into distinct metrics and arranged them into a systematic questionnaire for expert review during the various stages of paddy farming. Expert assessments were analyzed using the MDS approach with the Rapfish method to quantify and interpret sustainability index scores. Calculated sustainability index results are presented in Table 3.

The MDS analysis indicates that sustainability performance in paddy farming management is 46.59% on a 0-100 scale. With a squared correlation coefficient (R^2) below 0.94, this score places paddy production in the low sustainability category. The sustainability index for each dimension is as follows: business opportunity (48.37%), institutional (43.91%), environmental and agricultural (46.31%), social (44.34%), and agrotechnology (50.07%). Fig. 2 and Table 3 provide a summary of the sustainability status across all assessed dimensions.

Agrotechnology dimension

Agrotechnology enhances people's welfare by boosting productivity, incomes, food security, and sustainability, especially in rural communities. Nonetheless, effective execution depends on

Table 1: The leverage factor's parameter values

No.	Leverage value	Group	Definition
1	> 8.0%	Significant	Dominant and critical sustainability
2	2-8%	Influential	Moderate to strong Influence
3	<2.0%	Neutral	Negligible

Table 2: Dimensions and attributes

Agrotechnology	1	Derivative products
	2	Digitalization of administration
	3	Rice processing
	4	Rice quality monitoring system
	5	RMU facilities
	6	Post harvest technology
	7	Rice storage infrastructure
Social	8	Human resources (HR) competence
	9	HR competency map
	10	Training
	11	Well-being and motivation
	12	Farmer empowerment
	13	Community involvement
	14	Corporate social responsibility (CSR)
	15	Partnership
Environmental and agricultural	16	Organic and inorganic waste management
	17	Use of environmentally friendly technology
	18	Water and soil pollution control questionnaire
	19	Water use efficiency questionnaire in agriculture
	20	Integrated environmental and agricultural management plan
Institutional	21	Good corporate governance (GCG) policy
	22	Enterprise risk management (ERM)
	23	5-Year business plan
	24	Establishment of an internal monitoring unit
	25	Quality management system
	26	Collaboration with government and private institutions
	27	Company regulations and legality
	28	Involvement in downstream policy
	29	Monitoring and evaluation of business performance
	30	Development of standard operating procedure (SOP) for operations and finance
Business opportunity	31	Production and marketing capacity of Perumda Agro Sukabumi rice
	32	ROE contribution to regional income
	33	Effectiveness of warehouse asset utilization
	34	Efficiency of financial and administrative systems
	35	Ability to face financial risks
	36	Competitiveness of local rice products
	37	Optimization of postharvest process
	38	Sustainable business partnership

Table 3: Summary of sustainability index scores and associated data quality levels

No	Dimension	Stress (S)	R^2	Index (%)
1	Agrotechnology	0.16	0.94	50.07
2	Business opportunity	0.14	0.95	48.37
3	Institutional	0.15	0.95	43.91
4	Social	0.15	0.94	44.34
5	Environmental dan agricultural	0.16	0.93	46.31
Average		0.15	0.94	46.60

sufficient access, education, and infrastructure to avert the expansion of inequality. The MDS result indicates that the agrotechnology dimension achieved a 50.07% sustainability index, reflecting moderate sustainability in Sukabumi's rice-based agricultural systems. According to the study by Rachman *et*

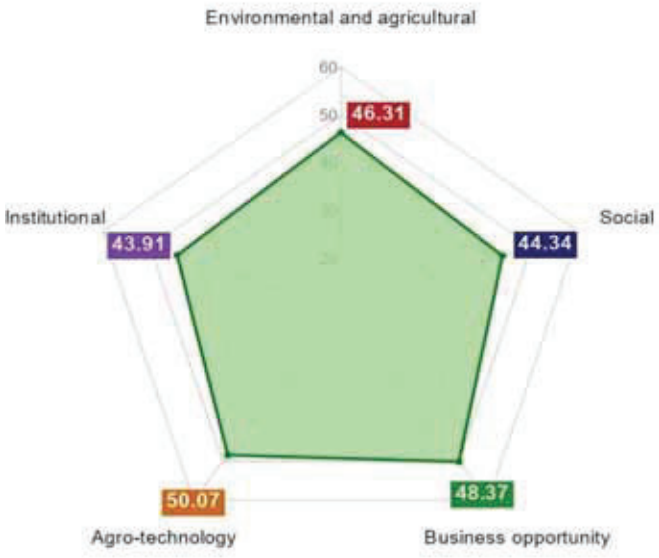

Fig. 2: Sustainability score of rice farming in Perumda Agro Sukabumi

al. (2022), the technological sustainability score is notably higher at 61.76% compared to the 46% score found in this study conducted in Sukabumi. This difference reflects faster adoption of improved rice varieties and modern cultivation practices in Bandung. Meanwhile, Sukabumi continues to face limitations in post-harvest infrastructure investment and structured technology dissemination. This disparity indicates a quicker embrace of enhanced rice varieties and contemporary farming techniques in Bandung. In contrast, Sukabumi faces constraints in post-harvest infrastructure investment and organized technology dissemination. The dimension significantly boosts production efficiency, postharvest processing, and rice-derived product development. Farmers' uptake of technology continues to be minimal, primarily due to insufficient infrastructure, restricted financial access, and the lack of structured technical support frameworks. The study identifies the top three leverage attributes in the technology dimension: administrative digitalization (1.69%), RMU facilities (1.38%), and rice-derived product development (1.25%) (Fig. 3). The evidence points to the necessity of specific advancements in digitalization and innovation to tackle challenges and boost sustainability performance. These technology drivers significantly enhance the efficiency of integrated agricultural activities and strengthen agro-industrial firms.

The digitalization of administration represents the most significant factor within the technology sector, emphasizing its importance in improving market transparency and operational efficiency. Digital technology enables real-time recording of harvests, sales transactions, and inventory, all of which facilitate data-driven decision-making. It also offers significant opportunities to boost production capacity in regional public rice enterprises by streamlining operations, reducing post-harvest losses, and enhancing supply chain transparency. Tools such as real-time monitoring systems, digital inventory management, traceability platforms, and online marketing apps can optimize production planning, reduce inefficiencies, and improve market access. Furthermore, the incorporation of sophisticated tools like AI-driven forecasting models, IoT-enabled monitoring systems, and remote sensing tools can significantly improve sustainability results by optimizing resource utilization, enhancing planning processes, and bolstering climate resilience. For Perumda Agro, integrating these digital solutions enables better demand forecasting, stronger farmer coordination, and more effective post-harvest facility use, supporting a transition toward a more sustainable and competitive rice system. Research indicates that digital platforms, particularly

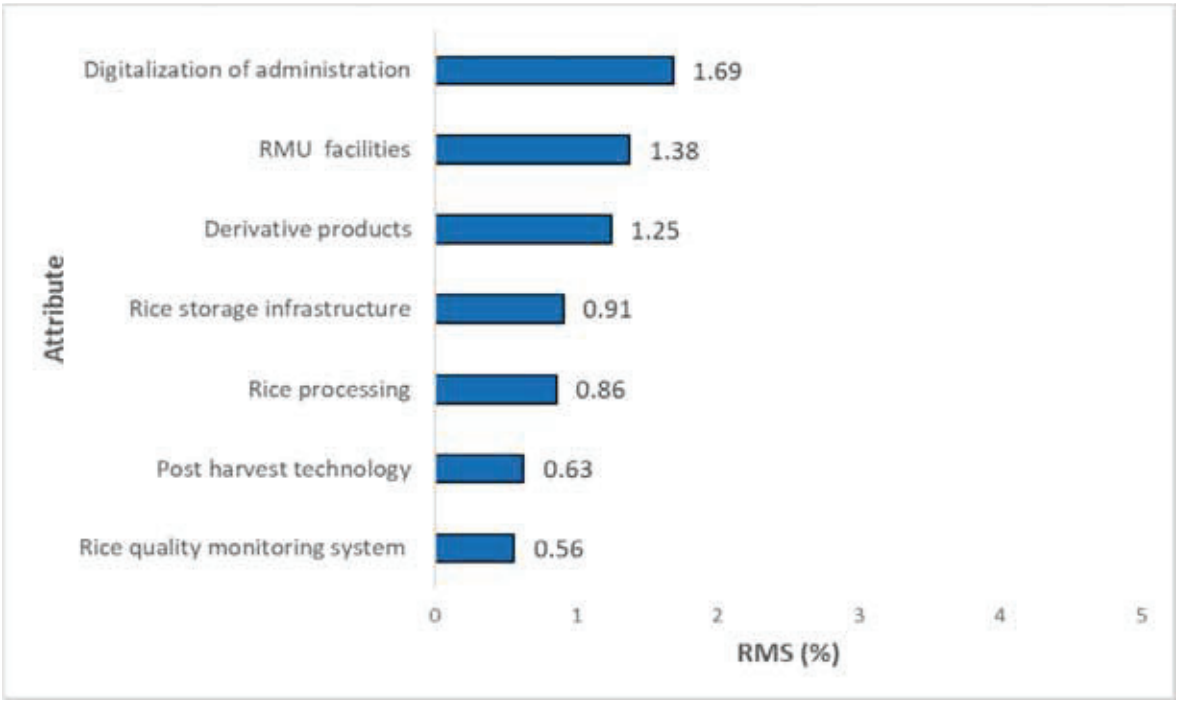

Fig. 3: Leverage of the agrotechnology dimension

mobile applications, enhance the involvement of smallholders in agricultural value chains by providing timely updates on market conditions and prices (Gumbi *et al.,* 2023). Nevertheless, in Sukabumi, farmers continue to use conventional practices due to low digital literacy and limited internet availability in rural areas (Sheikh and Berényi, 2023). This highlights the necessity for organized training and financial support to bridge the digital gap and promote more cohesive, market-oriented agricultural practices. The second most important trait is the presence of RMU facilities. RMUs play a vital role in maximizing postharvest efficiency, improving rice quality, and increasing product value. Most farmers must ship the paddy out of the region for milling, incurring additional logistics costs and creating a fragmented supply network. Consequently, farmers are compelled to sell unprocessed paddy to brokers at reduced prices because of insufficient local milling facilities. Previous research indicates that adopting centralized and technologically advanced milling facilities can reduce grain losses and enhance product standards. Such facilities also expand opportunities for farmers to engage in premium-value supply chains (Ikhwan *et al.,* 2024). Furthermore, expanding the range of rice-based products is crucial for improving farmers' income stability beyond just post-harvest productivity. Products including rice flour, organic rice, fortified rice, and rice-based snacks possess a higher market value than unprocessed paddy. However, in Sukabumi, the potential for developing this sector remains underutilized due to a lack of processing facilities and non-compliance with Indonesian National Standards (SNI). Enhancing local processing capabilities may allow farmers with opportunities to reach higher-value markets while decreasing their dependence on fluctuations in raw rice prices. Studies indicate that product diversification reduces market vulnerability and enhances small-scale farmers' economic stability (Manda *et al.,* 2021; Kyaw *et al.,* 2018). Enhancing technology-related sustainability calls for developing SNI-compliant RMUs and strengthening digital literacy training for farmers and stakeholders. Support for developing localized rice-based product value chains is also essential. The partnership of public and private academic entities is vital for advancing technology transfer and reinforcing institutional strengths. These efforts make production more efficient and enhance

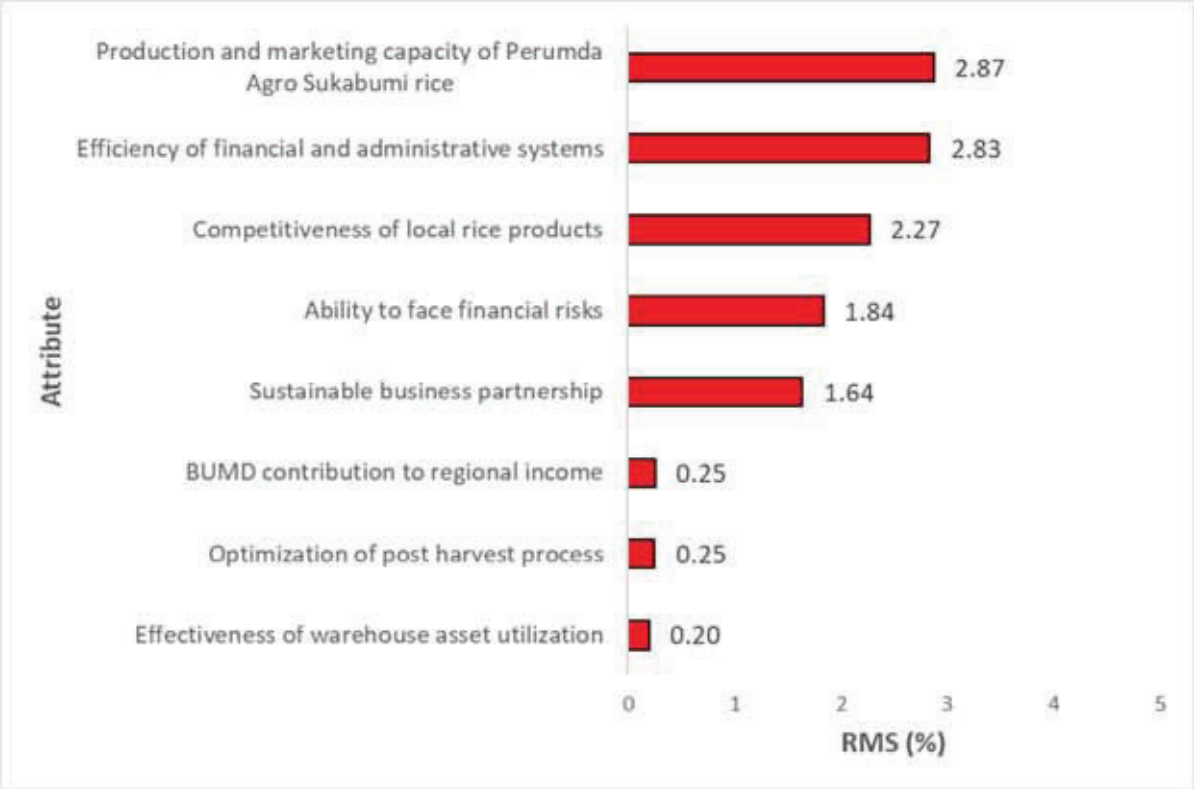

Fig. 4: Leverage of business opportunity dimension

the competitiveness of Sukabumi's agricultural commodities regionally and nationally. Through proper intervention, technological improvements can be a top driver of sustainable, inclusive, and adaptive agrarian development.

Business opportunity dimension

Rice farming provides avenues for growth in cultivation, supply of inputs, mechanization, processing, logistics, and the incorporation of technology. MDS analysis shows that the Business Opportunity dimension of Perumda Agro Sukabumi Mandiri has a sustainability index of 48.37%, indicating moderate sustainability (Fig. 4). The business opportunity dimension in this study scored higher than in Rachman *et al.* (2022) for Bandung (35.25%), suggesting marginally better business opportunities in Sukabumi. Nonetheless, both values continue to be low, underscoring ongoing difficulties in market access, value chain integration, and financial stability across the region. This aspect illustrates the structural obstacles present within Sukabumi's rice distribution framework, including inefficiencies in operations, difficulties in managing finances, and the inadequate use of government assets. The Introduction outlines these issues as key barriers to effective distribution. The primary attributes that hold influence in this Business Opportunity dimension include production and marketing capacity (2.87%) and the efficiency of financial and administrative systems (2.83%). These two aspects represent critical leverage points for targeted improvements.

Business opportunity largely depends on the efficiency of administrative and financial systems. Perumda Agro, as noted in the faces challenges such as limited implementation of digital systems in internal management and prolonged accounts receivable cycles. The internal documentation shows how some receivables may require over 60 days for collection. Furthermore, the documentation reveals that internal audits occur irregularly, and administrative paperwork remains weak. The enhancement of

financial transparency may be realized through the deployment of enterprise resource planning (ERP) systems that incorporate formal internal controls, in accordance with the best practices of modern agribusiness management (Laudon and Laudon, 2020). Perumda Agro also plays a significant role in producing and marketing. The production and marketing capabilities determine the degree of regional economic resilience. Sukabumi experiences volatile rice prices due to the weak bargaining position of farmers. Unhusked rice is frequently sent to other regions for milling and reimported for local consumption (Purwandoko *et al.,* 2024). The restricted production scale and insufficient market presence impede the competitiveness of local rice, particularly when contrasted with regions like Cianjur. Previous studies indicate that local products in price-sensitive markets are hampered by weak branding and poorly planned distribution networks (Bulambo *et al.,* 2023). Targeted investments in promotions, brand development, and market penetration (including e-commerce and digital marketing) are essential. The underutilization of several warehouse assets, particularly in Jampang Kulon, represents another critical issue addressed in the Introduction. Utilization rates below 60% suggest low logistical efficiency and high operating costs, primarily due to inadequate planning and limited working capital. Improving the efficiency of operations and the potential for rental income can be realized by optimizing warehouse assets via public-private partnership initiatives or by including them in wider logistics planning. Additionally these approaches can also fortify the resilience of regional supply chains (Mataia *et al.,* 2020). A mismatch between expenditure and income is evident in the contribution to local government revenue, which remains relatively low at below 5%. Fiscal imbalances result from poorly managed subsidies and unbalanced partnerships. Additionally, it has been highlighted that tighter financial planning and periodic evaluations of partnerships are essential, as shown by stakeholder interviews. Business policies focused on fiscal risk management are also necessary (Ibrahim and Agustina, 2024). Enhancing the economic sustainability of Perumda Agro Sukabumi Mandiri requires focused efforts on digitizing financial systems and strengthening market access through effective branding. Additional priorities include optimizing warehouse asset utilization and reforming business partnership policies. It is expected that these strategic actions will strengthen the company's financial status and substantially elevate its impact on the regional economic growth of Sukabumi.

Institutional dimension

The institution recorded a 43.91% sustainability index, which falls under the moderately sustainable category. The institutional sustainability score in this study is slightly lower than that reported by Rachman *et al.* (2022) in Bandung (48.11%). This resemblance points to mutual challenges in governance, risk management, and inter-institutional collaboration within rice farming operations in West Java. While the score reflects the establishment of some underlying institutional mechanisms, the comparatively low performance signifies serious problems in risk governance, assurance of quality, and stakeholder collaboration. The company, functioning as a regional public enterprise, must strike a balance between generating profit and providing public service, which calls for a solid institutional framework. The effectiveness of the current governance model is limited by unclear delegation of authority, a fragmented leadership structure, and insufficient autonomy in field-level decision-making. These restrictions compromise the responsiveness and adaptability of sustainability programs, especially in rural operational zones where contextual flexibility is essential (Rachman *et al.,* 2022). Enhancing governance by establishing clear accountability, engaging in participatory planning, and decentralizing authority would greatly enhance the implementation of strategic initiatives. MDS analysis identified three high-leverage institutional characteristics: including corporate risk management (1.40%), quality management system (1.10%), and Government and Private Institution Collaboration (0.98%). Corporate Risk Management, with the most substantial leverage in this sector (1.40%), indicates pressing financial control and asset protection challenges, as shown in Fig. 5. The business is encumbered by a substantial level of unpaid accounts receivable and unpredictable payment patterns, compromising its financial stability. These challenges are exacerbated by the company's lack of an integrated ERM system (Andersen and Young, 2023). Without proper procedures to evaluate, mitigate, and monitor financial risks, the company is exposed to fiscal instability. According

to the findings of Kulinich *et al*. (2023), effective ERM systems greatly enhance financial stability, particularly during times of economic volatility. Thus, constructing a digitalized risk register, regular internal risk reviews, and tightened partner vetting procedures should be prioritized to enhance the company's financial discipline and decision-making processes. The Quality Management System, with a leverage of 1.10%, highlights significant institutional vulnerabilities in standardization, documentation, and process consistency. Despite the existence of an application interface, the documentation is disjointed and lacks systematic integration into the core functions. The lack of ISO 9001 (compliant systems and irregular internal audits) further weakens process accountability. Research indicates that digitized quality management systems can improve regulatory compliance, operational transparency, and customer satisfaction (Delgado Mendoza *et al.,* 2023). Implementing a systematic quality framework with routine internal and external audits and KPIs is essential for ensuring compliance with standards. Such measures also help secure public trust in the operational integrity of Perumda Agro. Incorporating enterprise software can accelerate the implementation of corrective measures and enable real-time quality assessment (Mercado, 2024).

Collaboration with Government and Private Institutions, the third institutional trait (0.98%), underscores the need for stronger organizational coordination. Collaborations are commonly created under ambiguous conditions, lacking thorough evaluation systems. This sometimes results in financial losses from untrustworthy partners who fail to return capital or meet performance requirements. This pattern reflects poor due diligence and limited external governance oversight. Study conducted by Eshun *et al*. (2024) indicates that the long-term success of public enterprises is significantly influenced by strategic, mutually beneficial partnerships. Institutional collaboration can be strengthened through clear partnership policies, performance contracts, and cooperation with universities, Non-Governmental Organizations (NGOs), and the private sector. Such collaboration enables knowledge transfer, technological advancement, and diversified capital investment (Gottlieb *et al.,* 2018). Furthermore, enhancing the role of independent oversight mechanisms can strengthen accountability and avert the misuse of power in choosing partners (Reich, 2018). In conclusion, enhancing the institutional sustainability of Perumda Agro Sukabumi Mandiri requires targeted reforms in its key leverage points. These include implementing formalized risk management guidelines, establishing standardized and digital quality systems, and developing open collaboration mechanisms to strengthen the enterprise's operational base. Improvements of this nature are crucial for ensuring financial robustness and aligning the company with the objective of fostering regional economic growth. This method highlights the importance of good governance and the foundations of institutional development.

The most efficient strategic actions for fostering institutional reform and sustainable resource management entail the establishment integrated risk and quality management systems. They also focus on bolstering governance through more defined accountability and decentralized authority, along with advancing environmental compliance. Implementation should focus on digitalization, capacity building, and consistent standards enforcement. Cross-sector collaboration, particularly with government bodies, private firms, academia, and NGOs, should be formalized through transparent, performance-based partnerships to drive innovation, improve resource efficiency, and strengthen long-term institutional resilience.

Environmental agricultural dimension

Paddy field farming thrives when ecological sustainability and agricultural efficiency are integrated. Balancing both ensures higher yields and long-term viability, resource conservation, and resilience against climate change. Consequently, the environmental and agricultural factors significantly influence paddy field farming. The environmental and agricultural attributes of Perumda Agro Sukabumi Mandiri scored 46.31% in the MDS analysis, a moderate level of sustainability. The environmental sustainability index in this study (46.31%) was lower than that reported by Rachman *et al.* (2022) in Bandung (50.57%). This gap illustrates that the environmental management strategies in Sukabumi, especially concerning water use efficiency and waste handling, are underdeveloped and need focused improvement initiatives. The results suggest that baseline environmental awareness exists, but further

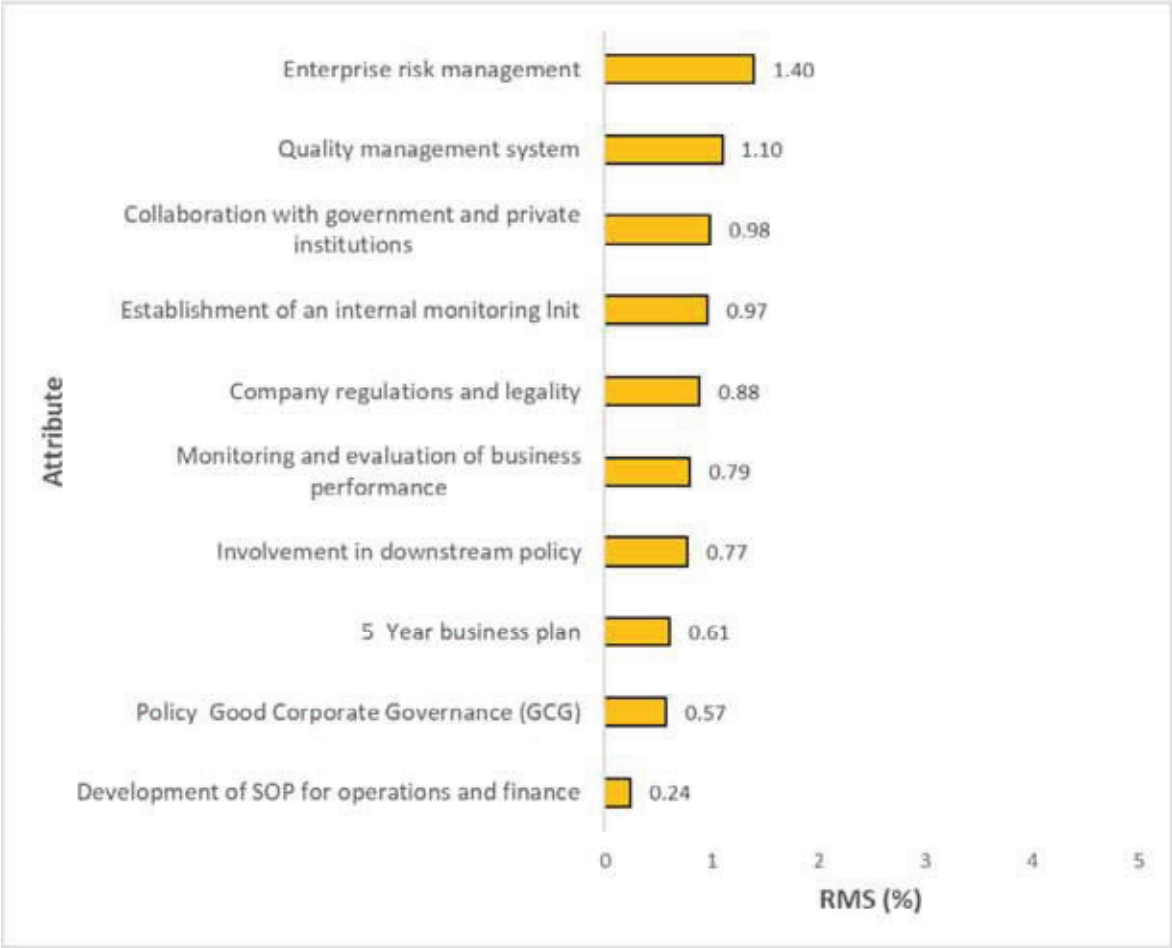

Fig. 5: Leverage of institutional dimension

analysis indicates that environmental practices require development and are not yet institutionally prioritized. Fig. 6 shows that among the five scored characteristics, the most impactful, based on leverage analysis, are environmentally friendly technology (4.92%), water use efficiency (2.93%), and waste management (2.67%). These areas represent priority targets for improving environmental performance.

The leading trait in environmental and agricultural practices is the implementation of climate-responsible technology. It has leverage value of 4.92%, highlighting its prominence in delivering sustainable farming practices. Even with such high importance, adoption of the technology is negligible. The reasons for such neglect are three-pronged. First, the prevailing agricultural techniques in Sukabumi are predominantly traditional, with minimal signs of environmental harm, which fosters the view that there is no pressing need for transformation. Second, most stakeholders, most prominently at the enterprise level, are interested in profitability in the short run, and environmental technology is seen as an expense rather than an investment opportunity. Third, the general public, farmers, and local actors are ill-informed of the long-run value of holistic environmental practices. These challenges have restricted the implementation of environmentally friendly technologies including low-emission equipment, bio-based fertilizers, and precision irrigation. Yet, such innovations are proven to reduce environmental impacts while enhancing productivity (Liu *et al.*, 2023). Government and enterprise driven incentives, such as subsidies, awareness campaigns, and integrating sustainability into operational KPIs,

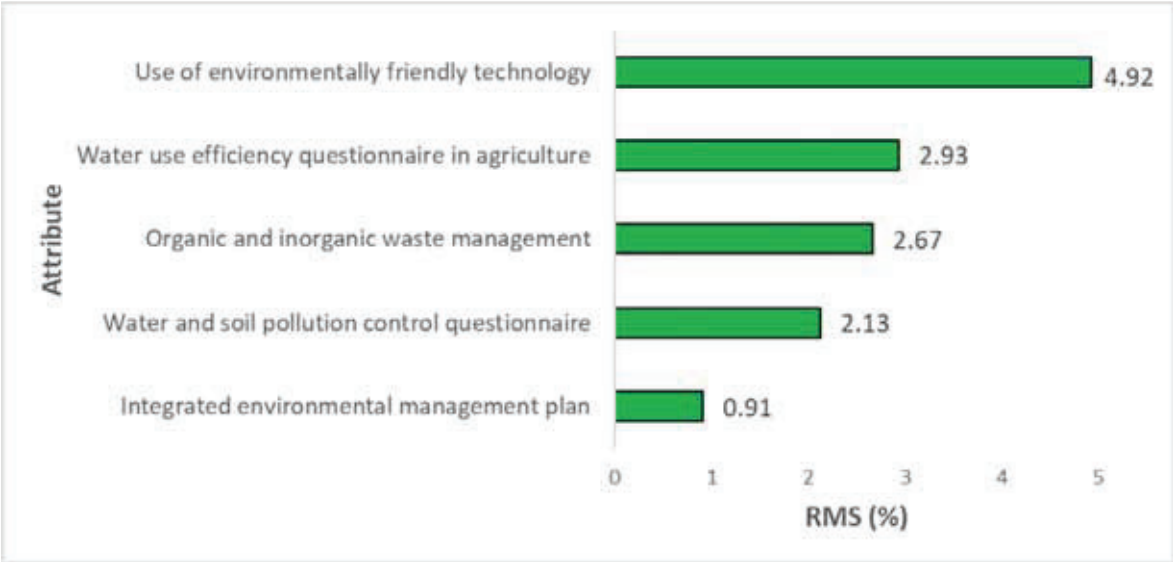

Fig. 6: Leverage of environment and agricultural dimension

are essential to shift this paradigm (Bakar *et al.,* 2020). Soil and water pollution control is closely linked to water use efficiency (2.93% leverage), exhibiting a leverage of 2.13%. These indicators point to essential but neglected aspects of sustainable rice cultivation. The region still relies heavily on traditional irrigation, and excessive dependence on seasonal rains undermines water supply predictability. Inefficient water distribution systems cause both wastage and reduced efficiency. Furthermore, the failure to implement monitoring systems for chemical runoff and nutrient leaching hastens the rapid degradation of land over time. Investments in drip irrigation, water metering, and training farmers in integrated water management can conserve many resources (Sasmita *et al.,* 2022). The use of reservoirs to collect rainwater during the rainy season provides reserves for the dry season (Erlambang *et al.,* 2022). Monitoring fertilizer and pesticide use helps prevent pollution and protect surrounding ecosystems from contamination (Tewari and Singh, 2024). Another urgent issue is waste management of organic and inorganic waste, with a leverage of 2.67%. Despite the considerable quantity of agricultural waste is generated, most of it is either incinerated or discarded without any processing. The lack of composting facilities and waste-to-energy options wastes the potential of circular agriculture. Studies have established that proper waste treatment not only minimizes environmental pressure but also produces valuable byproducts, including organic manure and biogas (Martey *et al.,* 2021). Such practices can increase income and promote sustainable agriculture (Widjaja *et al.,* 2024). The report identifies risks associated with climate change, including dependence on rainfed agriculture, water scarcity, and greenhouse gas emissions, it lacks the explicit integration of climate projection data or scenario-based modeling. Incorporating analytical tools such as climate risk maps, water stress scenarios, and crop yield simulations could enhance Perumda Agro's capacity to prioritize adaptive investments, design water-efficient systems, and strengthen risk governance mechanisms in alignment with SDG Target 13.2. The failure to incorporate such integration highlights a significant shortfall in the organization's planning for long-term resilience and climate adaptation. By adopting climate-informed tools such as downscaled rainfall simulations, evapotranspiration models, and seasonal temperature risk assessments, the enterprise could better forecast stress events, optimize adaptive irrigation, and prioritize infrastructure investment. As an illustration, multi-hazard risk maps alongside crop yield forecasting models have been effectively employed in analogous scenarios to steer adjustments in land use and the selection of crops

that are resilient to climate change (Sloat *et al.*, 2020). Furthermore, developing an enterprise-level climate risk framework, such as ERM integrated with climate data, would strengthen Perumda Agro's ability to respond to shocks, develop contingency plans, and attract green finance (Aggarwal *et al.*, 2018). This approach ensures the proactive embedding of resilience into operational workflows and aligns with Indonesia's National Action Plan on Climate Change (INAPCC). These environmental inadequacies conflict with Sukabumi's commitment to the SDGs, especially SDG 2 (Zero Hunger) and SDG 13 (Climate Action). The ecological practices of Perumda Agro are insufficiently aligned with Target 13.2 and Target 2.4 of the Sustainable Development Goals. Target 13.2 involves integrating climate policies into planning, while Target 2.4 focuses on establishing stable structures and achieving optimal food production. Moreover, the lack of optimization in land and water use, coupled with the failure to implement circular waste management practices, poses a significant risk to environmental sustainability and the sustained productivity of agricultural enterprises. In conclusion, although Perumda Agro Sukabumi Mandiri's current environmental sustainability status is moderate, it remains fragile and underleveraged. The enterprise must prioritize green investment, water-saving innovation, and structured waste recovery to safeguard ecological integrity and enhance agrifood system competitiveness. To incorporate sustainability into routine practices, it is vital to transform institutions with the support of awareness, incentives, and enforceable regulations. Strategic action on these leverage points can serve both environmental goals and regional economic resilience.

Social dimension

The social dimension of Perumda Agro Sukabumi Mandiri had an index of 44.34%, placing it in the lower moderate category. The social sustainability dimension in this study achieved a higher score than that reported by Rachman *et al.* (2022) in Bandung (30.79%). This implies a somewhat better engagement of farmers and local communities in Sukabumi. Despite the overall score is still low, it signifies the importance of further bolstering collective action, farmer organizations, and governance engagement. The results indicate insufficient progress by the company in providing inclusive and equitable benefits to employees, farmers, and the community. Despite having a dual focus on profitability and public value, the organization's social performance indicators show little progress. Human resource development and community participation have yet to be fully maximized. According to the MDS scores shown in Fig. 7, the top leverage points in the social aspect are employee morale and motivation (1.20%), empowerment of the farmers (1.16%), and training (1.10%). These leverage points highlight the most critical areas for intervention to significantly enhance the organization's social sustainability.

Employee well-being and motivation, with the highest leverage value of 1.20%, represent a cornerstone of internal productivity and organizational performance. Field observations demonstrate that many workers are missing formal performance incentives, adequate health coverage, and avenues for career development. Programs for training, career advancement, and performance-based rewards can boost employee satisfaction and engagement (Le *et al.*, 2021; Lemma and Sharma, 2024). The lack of formal reward mechanisms and poor work-life balance contribute to reduced morale and higher turnover potential. Empirical research confirms that workplace motivation, driven by fair compensation, recognition, and psychological security, is positively associated with productivity and creativity (Sobaih *et al.*, 2024; Le *et al.*, 2021) . Perumda Agro should implement a structured performance review system, provide essential welfare services (health, insurance, transportation), and foster a collaborative work environment to address these issues. By prioritizing the well-being of employees, the company can develop a more loyal and productive team that can fulfill its overarching sustainability objectives. The second key attribute is farmer empowerment (1.16%), which remains a significant yet underdeveloped aspect of the company's engagement with agricultural communities. Although Perumda Agro aims to support local producers and stabilize prices, farmers still face significant challenges, including limited market access, price volatility, and inadequate post-harvest services. The unclear pricing of grains and the limited engagement of farmers in decision-making within the value chain obstruct their potential to reach economic independence. To address these challenges, Perumda Agro should expand market access through digital platforms and

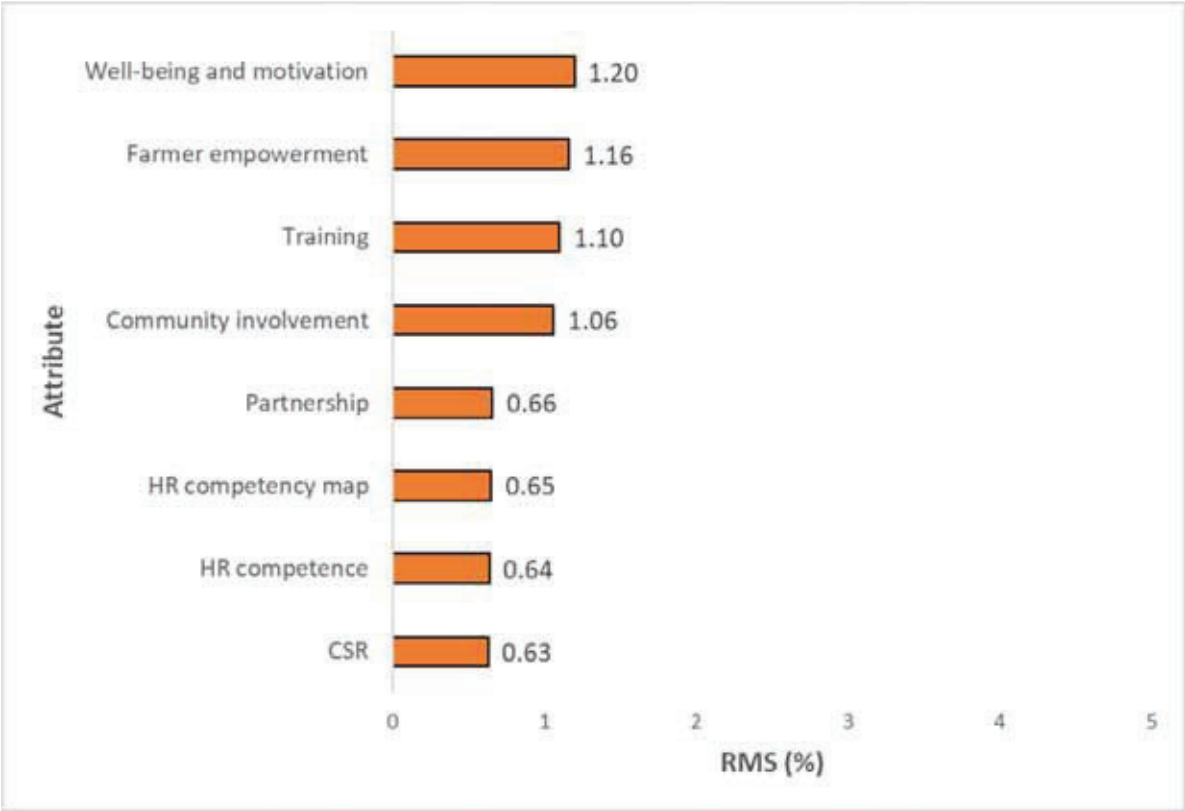

Fig. 7: Leverage of social dimension

partnerships with the modern retail sector (Veile *et al.,* 2022). Studies shows that contract farming, price guarantees, and co-management arrangements significantly improve farmers' income stability and productivity (Abebe *et al.,* 2016; Manda *et al.,* 2021). Additionally, affordable microcredit schemes (Balana and Oyeyemi, 2022), modern agricultural tools (Surendran-Padmaja *et al.,* 2025), and crop sales assistance programs (López *et al.,* 2024) are urgently needed. As a state-owned company, Perumda Agro should develop an inclusive procurement model, provide transparent market information, and involve farmer cooperatives in policy development. Such actions would mitigate the risks faced by smallholders while strengthening the long-term resilience of supply chains. The third key attribute (1.10%) is Training, which is critical for developing technical expertise and adaptive capacity among both employees or farmers. Currently, training initiatives are conducted in a haphazard manner and fail to correspond with real-world issues such as climate variability, digital transformation, and shifting market demands. Evaluation data show low participation rates and a lack of structured post-training assessments. This undermines the effectiveness of training as a mechanism for sustainable development. Consistent, context-specific, and technology-supported training programs have significantly improved output and accelerated the adoption of environmentally friendly practices (Piñeiro *et al.,* 2020; Jat *et al.,* 2025). Perumda Agro should develop an accessible training structure incorporating digital platforms, on-farm demonstrations, and modular content. Consistent feedback mechanisms and impact evaluations are crucial for guaranteeing that training results in enhanced practices and operations. In conclusion, Perumda Agro Sukabumi Mandiri's social sustainability will be strengthened by prioritizing an organized training framework, farmer empowerment, and workforce health and well-being. Organizations that invest in human and social capital are likely to present a fairer value proposition to their internal

and external stakeholders, positioning themselves as strong, socially aware contributors to regional advancement. To ensure actionable outcomes, it is important to distinguish between short-term operational measures such as implementing digital risk registers, conducting routine audits, standardizing internal SOPs, providing farmer training, and ensuring timely access to seeds and fertilizers—and long-term structural reforms that include policy realignment for inter-agency collaboration, increased local governance autonomy, and embedded accountability systems across institutional levels.

Policy implications and recommendations

Addressing the sustainability challenges identified in this study requires targeted policy interventions and strategic initiatives relevant to Perumda Agro Sukabumi Mandiri and similar regional enterprises. To boost agrotechnological sustainability, it is essential to invest in advanced rice milling units (RMUs) and post-harvest processing facilities, with the support of accessible credit options and partnerships between public and private entities. Demonstration plots and focused training programs can help accelerate the adoption of efficient cultivation practices and close farmers' knowledge gaps. To strengthen business opportunities, local government and Perumda Agro should expand digital marketing platforms, implement real-time transaction monitoring systems, and improve infrastructure in remote areas to reduce transport costs and improve market access. Collaboration should focus on developing localized value-added processing to increase farmers' bargaining power and regional competitiveness. Institutional reform requires establishing structured risk management frameworks, enhancing quality control systems, and strengthening inter-agency coordination to ensure policy coherence. Main priorities consist of creating distinct accountability frameworks, optimizing bureaucratic workflows, and fostering transparency in the decision-making process. Cross-sector collaboration with government agencies, enterprises, research institutions, and farmer organizations is essential to overcome fragmented governance and build resilient institutional capacity. For environmental sustainability, policies should promote efficient irrigation systems, integrated pest management, and improved waste management infrastructure. Essential actions consist of providing incentives to encourage the use of green technologies, facilitating training in climate-smart methods, and enhancing the enforcement of environmental regulations. Coordinated planning across agricultural, environmental, and infrastructure agencies is needed to align regional development with sustainable resource use. Finally, improving social sustainability depends on empowering farmer organizations and cooperatives, ensuring participatory governance structures, and expanding extension services to build capacity and trust. Emphasizing inclusive decision-making will strengthen collective bargaining and better align local practices with sustainability goals.

CONCLUSION

The multidimensional scaling (MDS) framework effectively evaluated the sustainability of rice-based agricultural systems in Sukabumi Regency. The current sustainability status is moderate, showing uneven progress across five essential dimensions. While agrotechnology and business opportunity exhibit marginally better scores, institutional and environmental-agricultural aspects perform weakest. These findings highlight a disparity between the intended policy objectives and the ability for implementation. The framework successfully translates complex sustainability metrics into actionable leverage points, enabling targeted diagnostics. Institutional underperformance reflects governance fragmentation, undefined accountability, and limited enforcement of risk and quality systems. These deficiencies undermine the enterprise's adaptive capacity and responsiveness to environmental and market disruptions. Environmental sustainability is further delayed by the inadequate implementation of low-emission technologies, poorly developed irrigation infrastructure, and the lack of effective circular waste management. These findings reveal that sustainability is not yet internalized as a strategic priority but remains externally driven and poorly resourced. Addressing these structural constraints requires institutional reengineering. Key priorities include developing integrated risk registers, embedding standardized quality protocols, and decentralizing operational authority. Collaborative alliances with governmental bodies, educational institutions, and the private sector can improve adaptive capacity and facilitate technological integration. Environmental reforms

must focus on promoting climate-smart practices, optimizing water use, and formalizing waste-to-value systems. These measures require policy coherence, financial incentives, and reliable data for monitoring and evaluation. Current priorities are centered on reinforcing institutional capacities, extending targeted training for farmers, and upgrading key infrastructure. Long-term transformation depends on cross-sector collaboration to harmonize mandates, promote transparency, and institutionalize accountability. Implementation should leverage interagency platforms and multi-stakeholder governance structures to bridge knowledge gaps and resource fragmentation. The MDS-based diagnostic approach contributes more than an evaluative tool; it outlines a roadmap for institutional transformation and environmental stewardship. The framework exposes systemic hindrances to sustainability and determines significant interventions with high leverage. These insights enable decentralized agricultural enterprises to align more effectively with the Sustainable Development Goals, particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals). Replicating this approach across similar agroecological zones can accelerate the transition toward inclusive and climate-resilient agri-food systems.

AUTHOR CONTRIBUTIONS

A. Riyanto developed the initial study plan, and critically analyzed the substantive scientific content of the manuscript. U.N. Thiyas was responsible for the overall conceptualization, literature review, project administration, supervision of data collection, development of the MDS methodology, data analysis and visualization, contributed to map development, interpretation of findings, manuscript drafting, editorial inputs, literature curation including hyperlinks, revision processes, and final submission of the manuscript. F.E. Widjaya facilitated institutional collaboration between BRIN and the Sukabumi local government, co-drafted the manuscript, a comprehensive evaluation of the manuscript's coherence and quality, and revision. E. Widjaja carried out field data collection and survey implementation and contributed to manuscript drafting. Suryani participated in field data collection and co-authored the manuscript. R. Diastuti was responsible for field data gathering, manuscript writing, and revisions. Y.M. Erlambang refined the manuscript formatting and co-authored the manuscript. N. Abbas contributed critical manuscript review. S.E.Y. Trihadi provided critical manuscript review and W. Sulistiono provided critical manuscript review. All authors have read and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
ALSCAL	Alternating least squares scaling
CSR	Corporate social responsibility
CO_2e	Carbondioxide equivalent
ERM	Enterprise risk management
ERP	Enterprise resource planning
GCG	Good corporate governance
ha	Hectare
HR	Human resources
INAPCC	Indonesia's National Action Plan on Climate Change
km^2	Square kilometres
MDS	Multidimensional scaling
NGO	Non-governmental organizationso not
Rapfish	Rapid appraisal for fisheries
RMU	Rice milling unit
RAE	Regional agriculture enterprise
R^2	Squared correlation coefficient
S	Stress
SNI	Indonesian national standard
SOP	Standard operating procedure
SDG	Sustainable development goal

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CASE STUDY

Climate change impact perception and agricultural adaptation in a coastal region

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ABSTRACT

BACKGROUND AND OBJECTIVES: Climate change perception plays a significant role in shaping agricultural households' adaptation strategies. Despite this, there is a lack of extensive empirical research exploring the link between perception and adaptation. This study aims to explore how farmers' perceptions of climate change influence livelihood adaptation behaviors in Vietnam's Mekong Delta, specifically investigating psychological factors as key determinants of adaptive capacity. This study intends to bridge the gap in comprehending perception-driven adaptation strategies based on perception in agricultural systems susceptible to climate impacts

METHODS: This cross-sectional study was conducted in Thanh Phu District, Ben Tre Province, Vietnam. The district is strategically located between the Ham Luong and Co Chien rivers. The district spans 425.7 square kilometers with a population density of 300 people per square kilometers and is particularly susceptible to the impacts of climate change. Projections suggest that 45 percent of residents could face flooding by 2100 due to sea level rise. Primary data were collected in January 2024 through a structured questionnaire survey. The survey was administered to 200 agricultural households. Five municipalities from three different ecological regions were chosen through simple random sampling. The study targeted household heads engaged in crop cultivation, livestock, aquaculture, and mixed farming systems. The 33-item questionnaire covered demographic characteristics, livelihood activities, climate change perceptions, and adaptation strategies. Data analysis applied multivariate logistic regression. This investigated the connection between 32 independent variables classified into five domains. These domains included socio-economic factors, perceived resource quality status, perception of climate change manifestations, perception of climate impacts on natural resources, and impacts of climate change on livelihoods. Seven binary-coded dependent variables that signify adaptation strategies were examined. These included change in production, increased production cost, increased labor input, livelihood transition, change in location, livelihood maintenance, and other adaptations. Model performance was evaluated using Nagelkerke R^2, Area under the curve from receiver operating characteristic analysis, and percentage correct classification. Statistical significance was considered at the $p < 0.05$ level.

FINDINGS: Findings indicate that the awareness of climate effects on livelihoods serves as the most significant predictor of adaptive behavior. It shows strong negative associations (Odds ratio = 0.254-0.552, $p < 0.001$) across multiple strategies. Conversely, perception of climate change manifestations correlates positively (Odds ratio = 2.007-2.401, $p < 0.05$) with adaptive strategies. Traditional socioeconomic variables exhibited minimal influence compared to perceptual factors. The models achieved strong performance indicators (Nagelkerke R^2 = 0.70-0.75; Area under the curve = 74-89 in percent). Production-focused strategies demonstrated highest predictive accuracy.

CONCLUSION: The outcomes underscore the importance of perception as a major catalyst for adaptation, surpassing the effects of socioeconomic factors. These findings advocate for enhanced climate communication and education to foster proactive adaptation. This study presents empirical evidence aimed at shaping sustainable policy frameworks for the coastal delta regions of Vietnam. In these regions, the adaptation to climate change is still quite limited .

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INTRODUCTION

Contemporary climate change research emphasizes modeling climate extremes, assessing impacts, and developing adaptation and mitigation strategies (Schipper *et al.,* 2022; IPCC, 2021; Holman, 2018; Hoque *et al*., 2019). Despite this, investigations into how households perceive their livelihoods and adapt are limited, primarily due to a lack of sufficient empirical data, the unavailability of behavioral models, and inadequate connections between science and policy (Brown *et al*., 2017; MONRE, 2022). Climate change perception critically influences household adaptation capacity. Brown *et al*. (2017) emphasize that adaptation depends on individuals' understanding of risks and opportunities, with farmers showing heightened perception often adopting proactive measures such as adjusting cropping systems or transitioning to sustainable practices. Small-scale households face high vulnerability to extreme events like droughts, floods, and salinity intrusion, where their ability to adapt is affected by natural conditions and their perception of risk (Holman *et al*. 2018). Studies in Bangladesh's coastal communities demonstrate that farmers with strong perception diversify income, enhance irrigation, or adopt smart agriculture (Hoque *et al.,* 2019). However, perception alone proves insufficient without financial, technical, or policy support (Mallick *et al.,* 2011; Manirakiza *et al.,* 2020). Climate change perception varies globally, influenced by education, farming systems, resource access, and socio-cultural factors (Lee *et al*., 2015; Capstick *et al.,* 2015; UNDP; University of Oxford, 2024). ADB (2024) indicates that over 90 percent (%) of farmers in Bangladesh, Indonesia, and Vietnam perceive temperature or rainfall shifts. The effects of climate change on agriculture are substantial, with higher temperatures, inconsistent rainfall patterns, and salinity intrusion contributing to lower yields of essential crops (Le and Nguyen, 2025). In Vietnam, the Philippines, Thailand, and Myanmar, 1 degree Celsius (°C) temperature increase above 30°C could reduce rice yields by 10% (ADB, 2024; IPCC, 2021). Intensifying storms, floods, and salinity intrusion further threaten crops and infrastructure, particularly in Vietnam's Mekong Delta, jeopardizing millions of farmers' livelihoods (Habib-ur-Rahman *et al.,* 2022). In spite of comprehensive research on climate change, there is still a scarcity of studies focusing on farming households' perceptions and their adaptation decisions (Cologna and Siegrist, 2020; Kraklow *et al.,* 2024; Abebaw, 2025). Previous research has primarily employed logistic regression models to identify factors influencing adaptation strategy selection (Bryan *et al*. 2013; Deressa *et al*. 2009; Onyekuru and Marchant 2017) and Ricardian approaches to evaluate adaptation effectiveness (Deressa and Hassan 2009; Huong *et al.,* 2019). However, these studies focus on demographic factors rather than perceptual drivers of adaptation behavior (Grothmann and Patt, 2005; Mertz *et al.,* 2009; Bryan *et al.,* 2009; Fahad and Wang, 2018). This study strays from standard practices by probing into perceptual influences as psychological catalysts for adaptation behavior, particularly investigating: i) socio-economic factors (SE); ii) perception of resource quality status (PRQS); iii) perception of climate change manifestations (PCCM); iv) perception of climate change impacts on natural resources (PICNR); and (v) impacts of climate change on livelihoods (ICCL). Using multivariate logistic regression, the study evaluates adaptive capacities including change in production (CP), increased production cost (IPC), increased labor input (IL), livelihood transition (LT), change in production location (CL), livelihood maintenance (LM), and other adaptations (OA). This current study aims to investigate how farmers' perceptions of climate change affect their strategies for adapting their livelihoods, with a special emphasis on the psychological factors that influence adaptive capacity. This study was conducted in Thanh Phu District, Ben Tre Province, located in Vietnam's Mekong Delta region, in 2023 to 2024.

MATERIALS AND METHODS

The research questions

1) How do farmers' perceptions of climate change manifestations influence their choice of livelihood adaptation strategies?

2) To what extent do socio-economic factors moderate the relationship between climate change perception and adaptation behavior?

The study hypotheses

Hypothesis 1. Farmers with higher perception of climate change manifestations are more likely to adopt proactive adaptation strategies.

Hypothesis 2. Socio-economic factors (farming experience, household income, farm size, production

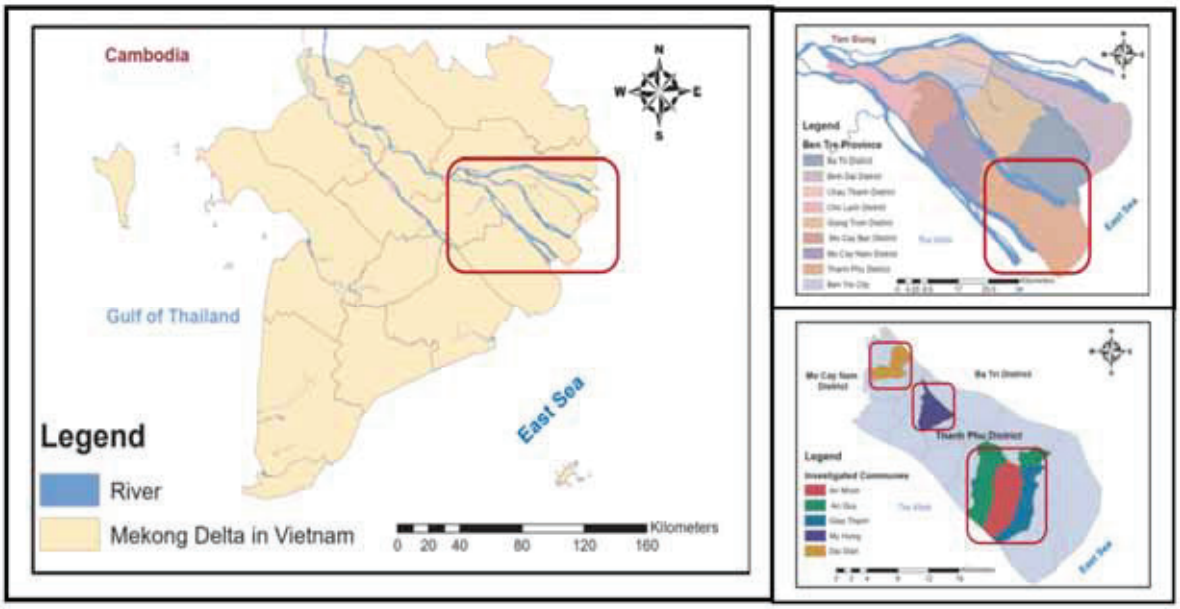

Fig. 1: Geographical location of household survey interviews in Thanh Phu District, Mekong Delta region, Vietnam

costs, and cropping frequency) moderate the relationship between climate change perception and adaptation behavior among farmers.

Study area and data collection

Thanh Phu District, located at the southernmost extent of Ben Tre Province, is situated between the Ham Luong and Co Chien branches of the Tien River system in the Mekong Delta (Fig. 1). Its coastal placement significantly increases its susceptibility to saltwater intrusion and the behavior of brackish water. Encompassing a natural area of 425.7 square kilometers (km²), which constitutes approximately 18% of the province's total land area, the district supports a population density of approximately 300 inhabitants per km². Under the A1F1 climate change scenario (MONRE, 2020; 2022), Thanh Phu faces severe impacts, with projections indicating that by 2100, approximately 45% of its population could be vulnerable to flooding due to sea-level rise (World Bank, 2024). Furthermore, the mainly farming-based livelihoods of the residents are facing growing challenges from environmental factors, including saltwater intrusion, flooding, soil erosion, and the deterioration of natural resources. Long-term studies have identified significant transformations in land use and livelihood strategies across three ecological zones within the district. In the freshwater zone, agricultural systems have shifted toward integrated cropping models, such as coconut–cocoa and coconut–giant freshwater prawn systems, alongside freshwater aquaculture and livestock rearing (cattle and goats). The brackish water region has largely shifted to integrated shrimp-rice systems and intensive shrimp farming. In the saline water zone, rice cultivation has been completely replaced by mangrove–shrimp agroforestry, clam and blood cockle aquaculture, and expanded livestock production (Trang and Loc, 2022). These adaptive transitions emphasize the pressing requirement for extensive policy frameworks that merge strategic resettlement with sustainable livelihood diversification to bolster the resilience of local communities against rising climate-induced adversities.

Data collection

In 2023, Thanh Phu District recorded a population of over 146,000 individuals distributed across approximately 37,000 households, with more than 25,000 households engaged in agricultural activities, representing nearly 70% of the total (Trang and Loc, 2022). A survey conducted from December 2023 to January 2024 targeted heads of households dependent on agricultural livelihoods, employing direct, face-to-face interviews based on a structured questionnaire comprising 33 items. The questionnaire

addressed four primary domains; i) demographic characteristics of household heads, ii) attributes of household livelihoods, (iii) perceptions of climate change impacts and changes in natural resources, and iv) livelihood adaptation strategies in response to CC and environmental resource alterations. For the purpose of achieving an effective sample size, approximately 200 households were selected for the survey. In order to maintain the representativeness and statistical dependability of the collected data, the sample size was defined, which is frequently employed in large-scale quantitative sociological studies using Eq. 1 (Cochran, 1977):

$$n = \frac{N}{(1 + N * e^2)} \quad (1)$$

Where:

n is the sample size, N = 25,000 is the total number of households in the study population, and e = 0.07 is the margin of error (±7%). Applying the formula: n = 25,000 / (1 + 25,000 * 0.0049) = 25,000 / 123.5 ≈ 202.4.

With a ±7% margin of error, the optimal sample size is approximately 202 households. Surveying 200 households is thus appropriate, ensuring accuracy and representativeness, consistent with recommendations for sociological field research (Israel, 1992). Participants consisted of leaders from farming households who represented local agricultural practices, which included crop production (rice, vegetables, fruit trees), livestock, aquaculture, fisheries, services, and mixed systems. The survey targeted five communes (Giao Thanh, My Hung, Dai Dien, An Nhon, An Quy) across three ecological zones, selected via simple random sampling to ensure equal selection probability, enhancing objectivity and representativeness (Table 1). This probability sampling method is widely used in large-scale quantitative research (Cochran, 1977).

Application of multivariate logistic regression model

Univariate logistic regression and multivariate logistic regression are widely used statistical methods for analyzing binary dependent variables (Nelder and Wedderburn, 1972; Hosmer *et al.,* 2013). Univariate logistic regression investigates how a single independent variable influences the dependent variable, which makes it appropriate for basic research questions or initial hypothesis testing, given its straightforward implementation and interpretation (Menard, 2002). In contrast, multivariate logistic regression enables the simultaneous evaluation of multiple independent variables, allowing for the identification of the distinct effect of each factor while controlling for the influence of others (Peng, Lee and Ingersoll, 2002). Utilizing multivariate logistic regression improves the predictive accuracy of models and clarifies the intricate relationships between associated variables (Hosmer *et al.,* 2013). This method is favored in studies with multiple influencing factors as it effectively controls for confounding variables and assess the independent effects of each factor (Hosmer *et al*., 2013; Menard, 2002). In this study, seven climate change adaptation strategies were identified as dependent variables, including: i) Change in production (CP); ii) Increased production cost (IPC); iii) Increased labor input (IL); iv) Livelihood transition (LT); v) Change production location (CL); vi) Livelihood maintenance (LM); and vii) Other adaptation measures (OA) (Table 2). The category "No change in production" was used as the baseline group, representing households that did not adopt any adaptation measures. The 32 independent variables (Table 3) were organized into five categories using a binning/categorization technique (Han *et al*., 2011). In line with Ellis's (1998) livelihood framework, the formation of a baseline group allows for detailed and theoretically informed comparisons among diverse adaptation options. The adaptation strategies were coded as binary variables,

Table 1: Distribution of the survey sample across communes

Province	Commune	Male	Female	Total
Thanh Phu	Giao Thanh	31	9	40
	My Hung	32	7	40
	Dai Dien	28	13	41
	An Nhon	15	23	39
	An Quy	40	0	40
Total		200		

Table 2: Response variables describing household livelihood adaptation capacity and priorities

Response variable	Total "Yes" responses	Total "No" responses	% "Yes" responses	% "No" responses
CP	192	8	96	4
IPC	195	5	97.5	2.5
IL	196	4	98	2
LT	121	79	60.5	39.5
CL	113	87	56.5	43.5
LM	197	3	98.5	1.5
OA	199	1	99.5	0.5
Total sample (N)			200	

with a value of 1 assigned if the household adopted the corresponding adaptation measure and 0 if it did not. This coding approach aligns with the livelihood analysis framework proposed by Chambers and Conway (1991), which emphasizes the flexibility and adaptive capacity of households in responding to the impacts of CC.

Based on a survey questionnaire, the study identified five groups of factors comprising 32 independent variables (Table 3), reflecting public perceptions of CC impacts. These groups include; i) Socio-economic factors; ii) Perception of resource quality status; iii) Perception of CC manifestations; iv) Perception of the impacts of CC on natural resources; and v) Impacts of CC on livelihoods. In accordance with Tabachnick and Fidell (2014), variables were systematically coded and categorized for logistic regression analysis, employing dummy variables or effect coding for categorical variables. Multivariate logistic regression was selected for its ability to control confounding factors and assess the independent effect of each explanatory variable on adaptation decisions. This model evaluates hypotheses concerning the impact of risk and threat perceptions on adaptive behavior, alongside a comparison of these perceptions with other influencing factors (Grothmann and Patt, 2005). Additionally, it enables analysis of interaction effects among independent variables, offering deeper insights into the complexity of adaptation decision-making. For instance, the model can evaluate whether CC perceptions differentially affect adaptation behavior across income groups (Van Valkengoed and Steg, 2019). Recognizing the elements that shape decisions regarding livelihood adaptation is vital for anticipating how households and communities will respond to the effects of climate change. Key factors include perceptions of CC effects (e.g., rainfall changes, temperature increases, disaster frequency), socio-economic conditions (income, household size, resource access), and geographic and environmental factors (Below *et al.,* 2012; Bryan *et al.,* 2009). Logistic regression models estimate the probability of farmers adopting livelihood adaptation practices according to these inputs. Such predictions are vital for policy planning and designing interventions to enhance CC adaptation (Hosmer *et al.,* 2013).

Multivariate logistic regression model analyzes the perception of CC

The multivariate logistic regression model analyzing perceptions of climate change impacts and household livelihood adaptation capacity for this study is expressed by the logit function, using Eq. 2 (Deressa *et al.* 2009; Agresti, 2007; Bryan *et al*., 2013; Onyekuru and Marchant, 2017):

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \quad (2)$$

Where:

p is the probability of the event occurring (the adoption or selection of an adaptation strategy).

$\frac{p}{1-p}$ is the odds ratio.

$\ln\left(\frac{p}{1-p}\right)$ is the natural logarithm of the odds ratio (logit).

β_0 is the intercept coefficient.

$\beta_1, \beta_2, \ldots, \beta_k$ are the regression coefficients corresponding to the independent variables.

$x_1, x_2, \ldots, x_k$ are the independent variables influencing the decision to select an adaptation strategy.

The probability of the event occurring (p) can be

calculated, using Eq. 3 (Tabachnick and Fidell, 2014):

$$p = \frac{e^{\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_k x_k}}{1+e^{\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_k x_k}} \quad (3)$$

In logistic regression, the coefficient (β) is not directly interpreted as in linear regression. Instead, e^{β} represents the odds ratio, indicating the change in odds per unit increase in the independent variable (Szumilas, 2010). An odds ratio > 1 implies increased event probability, < 1 indicates decreased probability, and = 1 suggests no effect (Bland and Altman, 2000). Prior to conducting multivariate logistic regression aimed at analyzing household livelihood perceptions and adaptation to climate change, the independent

Table 3: Summary of the 32 independent variables used in the analysis

No.	Socio-economic (SE)	Description	No.	Perception of climate change manifestations (PCCM)	Description
1	Average monthly household income (AMHI)	Monthly household income-United States Dollar (USD)	17	Perceived impact of climate change on surface water quality	impact of climate change on surface water quality
2	Years of farming experience (YFE)	Years of farming experience	18	Perceived impact of climate change on groundwater quality	impact of climate change on groundwater quality
3	Number of crops per year (NCPY)	Number of crop seasons	19	Perceived impact of climate change on air quality	impact of climate change on air quality
4	Cultivated land area (CLA)	Cultivated land area-square meter	20	Perceived impact of climate change on cultivated soil quality	impact of climate change on cultivated soil quality
5	Production cost per crop (PCC)	Production cost per crop - USD	No	Impacts of climate change on livelihoods (ICCL)	Description
No	Perception of resource quality status (PRQS)	Description	21	Unseasonal rain reduces crop yield	Impact of unseasonal rain on crop yield
6	Perceived water quality	Assessment of surface water quality for livelihood	22	Unseasonal rain increases investment cost	Impact of unseasonal rain on investment cost
7	Perceived groundwater quality	Assessment of groundwater quality for livelihood	23	Unseasonal rain decreases income	Impact of unseasonal rain on income
8	Perceived soil quality	Assessment of soil quality for livelihood	24	Flooding reduces crop yield	Impact of flooding on crop yield
9	Perceived air quality	Assessment of air quality for livelihood	25	Flooding increases investment cost	Impact of flooding on investment cost
No	Perception of climate change manifestations (PCCM)	Description	26	Flooding reduces income	Impact of flooding on income
10	Impact of climate change-induced temperature variation	Impact of climate change-induced temperature variation on livelihood	27	Salinity reduces crop yield	Impact of salinity on crop yield
11	Impact of climate change-induced rainfall variation	Impact of rainfall variation on livelihood	28	Salinity increases investment cost	Impact of salinity on investment cost
12	Impact of climate change-induced storms	Impact of storms on livelihood	29	Salinity reduces income	Impact of salinity on income
13	Impact of climate change-induced drought	Impact of drought on livelihood	30	Drought reduces crop yield	Impact of drought on crop yield
14	Impact of climate change-induced floods	Impact of floods on livelihood	31	Drought increases investment cost	Impact of drought on investment cost
15	Impact of climate change-induced changes in river water levels	Impact of changes in river water levels on livelihood	32	Drought reduces income	Impact of drought on income
16	Impact of climate change-induced changes in salinity	Impact of climate change-induced salinity intrusion			

variables were tested for multicollinearity. Multicollinearity, where independent variables are highly correlated, can bias coefficient estimates, inflate standard errors, and reduce model reliability (Mansfield and Helms, 1982). Model goodness-of-fit and statistical significance were assessed to verify if independent variables explain the dependent variable and ensure predictive accuracy. The non-parametric Median Test, a variant of the Chi-square test, was used to compare medians across independent samples, using Eq. 4 (Siegel and Castellan, 1988):

$$\chi^2 = \frac{\sum_{i=1}^{k}\sum_{j=1}^{2}(O_{ij}-E_{ij})^2}{E_{ij}} \quad (4)$$

Where:

k is the number of independent samples.

Oij is the observed frequency in the *(i,j)* -th cell of the *k x n* contingency table.

Eij is the expected frequency in the *(i,j)* -th cell, computed, using Eq. 5 (Daniel and Cross,2013):

$$E_{ij} = \frac{R_i \times C_j}{n} \quad (5)$$

Prior to performing regression analysis, it is essential to verify the presence of multicollinearity, which occurs when independent variables exhibit a high degree of correlation. According to Mansfield and Helms (1982), multicollinearity can bias regression coefficient estimates and inflate standard errors.

The Variance Inflation Factor (VIF) is used to assess the degree of multicollinearity, using Eq. 6 (Kutner *et al.,* 2005):

$$VIF_j = \frac{1}{1-R_j^2} \quad (6)$$

Where:

$\mathrm{VIF_j}$ is variance inflation factor for $\mathrm{j-th}$ variable.

$\mathrm{R_j^2}$ is the coefficient of determination when regressing the j- th variance on all other independent variable.

According to O'Brien (2007), a VIF>10 indicates severe multicollinearity, warranting consideration of variable removal or combination. In order to identify the set of parameters for household livelihood adaptation that maximizes the likelihood of the observed data, parameters are estimated using maximum likelihood estimation (MLE) (McCullagh and Nelder, 1989). This technique, as implemented in the study, improves the estimation of regression coefficients while preserving statistical characteristics such as consistency, unbiasedness, and efficiency in binary data analysis (Hosmer *et al.*, 2013). Consequently, the log-likelihood function is calculated, using Eq. 7 (Hosmer *et al.*, 2013):

$$\mathrm{LL} = \sum_{i=1}^{n}[y_i \ln(p_i) + (1-y_i)\ln(1-p_i)] \quad (7)$$

Where:

$\mathrm{LL\ is\ the\ log-likelihood\ value.}$

y_i is the actual value of the dependent variable (0 or 1) for the $i-$th observation.

p_i is the predicted probability for the $i-th$ observation.

n is total number of observations.

The study also assesses the overall significance of the logistic regression model using the Likelihood Ratio Test. This assessment evaluates the compatibility of two models: the comprehensive model that incorporates all independent variables, and the null model that consists solely of the intercept without any explanatory variables, as outlined in Eq. 8 (Menard, 2002):

$$\chi^2 = -2(LL_0 - LL_1) \quad (8)$$

Where:

χ^2 is the Chi $-$ square test statist; c.

LL_0 is the log $-$ likelihood of the null model (containing only the intercept).

LL_1 is the log-likelihood of the full model (including the independent variables).

According to Peng *et al.* (2002), a p-value less than 0.05 indicates that the overall model is statistically significant, suggesting that at least one independent variable has a significant effect on the dependent variable. This facilitates the integration of explanatory variables within the regression model. Furthermore, to evaluate the appropriateness of a logistic regression model, considering that the dependent variable is binary (typically coded as 0 or 1), the coefficient of determination R^2, conventionally employed in linear regression, is not directly applicable for assessing

model fit. Alternative methods have been created to measure how much independent variables contribute to the variability observed in the dependent variable. Among the most commonly utilized metrics is the Cox and Snell R^2 coefficient which provides a robust measure of explanatory power, using Eq. 9 (Cox and Snell, 1981):

$$R^2_{Cox\ \&\ Snell} = 1 - \left(\frac{L_0}{L_1}\right)^{\frac{2}{n}} = 1 - e^{-\left(\frac{2}{n}\right)(LL_1 - LL_0)} \quad (9)$$

The Nagelkerke R^2 coefficient used as Eq. 10 (Nagelkerke, 1991):

$$R^2_{Nagelkerke} = \frac{R^2_{Cox\ \&\ Snell}}{1 - e^{\frac{2LL_0}{n}}} \quad (10)$$

A Nagelkerke R^2 value approaching 1 indicates superior model fit, demonstrating that the model robustly explains the variation in the dependent variable through the independent variables. The Cox and Snell R^2 and Nagelkerke R^2 coefficients, analogous to the coefficient of determination in linear regression, quantify the proportion of variance in the dependent variable accounted for by the logistic regression model. In this study, the Akaike Information Criterion (AIC) is utilized as a statistical measure for model evaluation and selection, allowing for the comparison of regression models, as presented in Eq. 11 (Akaike, 1974):

$$AIC = -2LL_1 + 2k \quad (11)$$

Where:

LL_1 is the logarithm of the likelihood function (log-likelihood) of the model,

k is the total number of estimated parameters in the model, including the constant.

Burnham and Anderson (2004) state that the AIC evaluates model optimality by balancing goodness of fit with model complexity. Models yielding lower AIC values are preferred, as they provide enhanced fit without superfluous parameters, thereby reducing the risk of overfitting and bolstering the generalizability of results. In order to rigorously evaluate the model's generalization ability with respect to unfamiliar data, this study utilizes a train/test split strategy. The training set is employed to estimate the parameters of the model, in contrast, the test set evaluates the predictive accuracy on data that is independent and has not been trained. The effectiveness of the model on the test set is evaluated using the logarithmic loss function, computed, using Eq. 12 (Burnham and Anderson, 2004):

$$\mathcal{L} = -\sum_{\{i=1\}}^{\{n\}} \left[y_i \ln\left(p_i\right) + \left(1 - y_i\right) \ln\left(1 - p_i\right) \right] \quad (12)$$

Where:

y_i is the actual value of the dependent variable $(0\ \text{or}1)$,

p_i is the predicted probability that $= 1$

n is the number of observations in the test set.

The effectiveness of the regression model is evaluated through the Odds Ratio (OR), which quantifies the impact of an independent variable on the likelihood of the dependent variable's occurrence. The OR is derived by exponentiation the regression coefficient β, using Eq., 13 (Hosmer *et al.*, 2013):

$$OR_j = e^{\{\beta_j\}} \quad (13)$$

The Odds ratio (OR) is interpreted as follows:

If OR>1, the independent variable is associated with an increased likelihood of the event occurring.

If OR<1, the independent variable is associated with a decreased likelihood of the event occurring.

If OR=1, the independent variable has no discernible effect on the likelihood of the event.

Additionally, the 95% Confidence Interval (CI) is employed to assess the precision of the OR estimate. For calculating the 95% confidence interval for the Odds Ratio, was used as Eq. 14 (Field, 2013):

$$CI_{\{95\backslash\%\}} = \left[e^{\{\beta_j - 1.96 \cdot SE_j\}}, e^{\{\beta_j + 1.96 \cdot SE_j\}} \right] \quad (14)$$

Where:

β: the estimated regression coefficient; SE: the standard error of β; e: Euler's number (≈2.718).

The marginal effects are employed to assess the impact of each factor on the likelihood of farmers adopting CC adaptation strategies. Derived from multivariate logistic regression, these coefficients indicate the change in predicted probability for a one-unit increase in an independent variable, assuming other variables remain unchanged (Hosmer *et al.*, 2013). According to Menard (2002), this technique

delivers a more straightforward interpretation of the practical impacts of independent variables in contrast to logit coefficients. Mathematically, the marginal effect is calculated using the Eq. 15 (Menard, 2002):

$$ME_j = \beta_j . \overline{P} . \left(1 - \overline{P}\right) \quad (15)$$

Where:

β_j is the regression coefficient of variable x_j, and $\overline{P}$ is the average predicted probability. When input data is standardized using StandardScaler, the marginal effect values reflect the standardized marginal impact of each variable on the probability of selecting an adaptation strategy. Receiver operating characteristic (ROC) curve analysis (Chaibub Neto *et al.,* 2024) was applied to evaluate the effectiveness of adaptation strategies by examining the trade-off between true positive rates (TPR) and false positive rates (FPR) across varying threshold values. For households reliant on their livelihoods, the threshold value C = 1 was established as the criterion for recognizing effective adaptation adoption. Model performance was quantified using the Area Under the Curve (AUC) metric derived from the ROC analysis.

RESULTS AND DISCUSSION

Characteristics of agricultural production households

Analysis results Table 4 revealed 70% of households possessed 5-10 years farming experience, while 27.5% had ≥11 years' experience. This population exhibited adequate expertise to detect environmental shifts over time, in line with recent studies suggesting that experienced farmers are more capable of recognizing the effects of climate change (Bryan *et al.,* 2013; Anzum *et al.,* 2023). Regarding livelihood models, 68% of farmers maintained 1-5 cropping seasons annually, reflecting moderate land and water resource utilization. Over 95% of households owned cultivated areas ≥5,000 square meters (m²), indicating production expansion potential with appropriate technical and infrastructural support (FAO, 2022). Production costs varied significantly: 40% of households spent <1,000 USD per season, while 33% invested >4,000 USD. These inequalities emphasize the differing financial strengths of households, which have a direct impact on their ability to adapt (Thornton *et al.,* 2014). Income analysis revealed 71.5% of households earned <400 USD monthly, with 21% earning <200 USD. This creates dual challenges: households experience severe CC impacts while possessing limited financial resources for adaptation measures (Vo *et al.,* 2021). The situation proves particularly severe for households in salinization, drought, or irregular rainfall-affected areas (Trang and Loc, 2022). The surveyed households show a high level of vulnerability to the effects of climate change, while also having substantial hands-on experience in effectively assessing extreme climate occurrences, including saltwater intrusion, drought, off-season rainfall, and flooding.

Analysis of natural environmental conditions and climate change impacts

According to the results depicted in Fig. 2, natural environmental factors play a crucial role in determining the agricultural production efficiency, especially given the growing and complex effects of climate change. Farmers' perception of the deteriorating quality of the natural environment is markedly pronounced. Only 55% of farming households rated surface water quality as "good," while for groundwater - a critical resource during the dry season - over 60% of households assessed its quality as "average" or "poor," highlighting the

Table 4: Descriptive statistics of predictor variables reflecting socio-economic characteristics

			SE		
No.	1	2	3	4	5
Predictor variable	Years of farming experience (YFE)	Number of crops per year (NCPY)	Cultivated land area-square meter (CLA)	Production cost per crop - USD (PCC)	Average monthly household income USD (AMHI)
Clustering: Frequency (%)	5–10: 140 (70%) 11–15: 21 (10.5%) 16–20: 5 (2.5%) > 20: 34 (17%)	1–5: 136 (68%) >5: 64 (32%)	0–1000: 1 (0.5%) 1000–5000: 9 (4.5%) 5000–10,000: 89 (44.5%) >10,000: 101 (50.5%)	200 USD to 1,000 USD: 80 (40%) 1,040–2,000 USD : 24 (12%) 2,040–4,000 USD: 30 (15%) >4,000 USD: 66 (33%)	400–600 USD: 36 (18%) 600–800 USD: 16 (8%) 200–400 USD: 101 (50.5%) <200 USD: 42 (21%) >800 USD: 5 (2.5%)

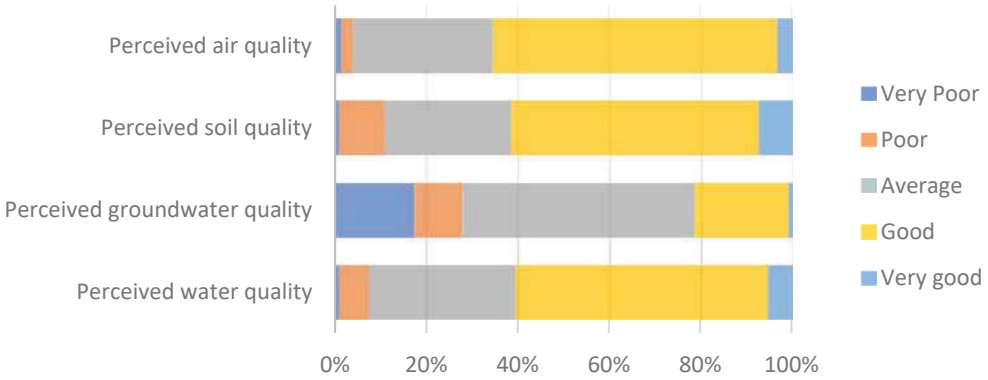

Fig. 2: Comparison of farming households' perceptions of resource quality status

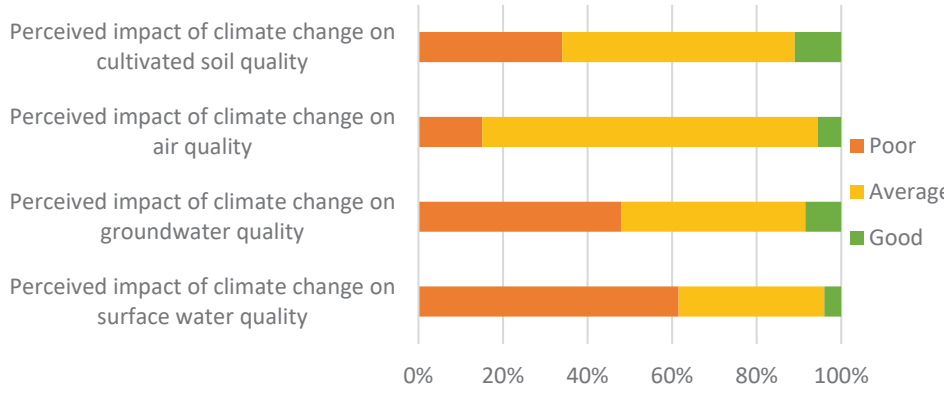

Fig. 3: Comparison of farming households' predictors of perceived climate change impacts on natural resources

risk of aquifer depletion driven by overexploitation and saline intrusion (Villholth, 2013). Furthermore, approximately 45% of households indicated that their cultivated soils are facing degradation and a decrease in fertility. In addition, air quality was rated poorly, with 33% of households observing a decline, possibly due to increasing temperatures and a reduction in vegetation cover (FAO, 2022).

Fig. 3 reveals that a majority of farming households perceive significant negative impacts of climate change on natural resources, with 61.5% specifically reporting surface water degradation. This perception is consistent with Vo *et al.,* (2021), who attributed such deterioration to disruptions in the hydrological cycle and rising sea levels in Thanh Phu. Furthermore, these findings align with FAO (2024), which emphasized that climate change accelerates soil degradation through erosion, organic matter loss, and salinization. Collectively, these environmental transformations highlight the way climate change is steadily weakening the ecological underpinnings of agricultural production systems.

Fig. 4 shows that, beyond general environmental conditions, the impacts of extreme climatic events are strongly perceived by farming households. In particular, 90.5% indicated an increase in temperatures, 82.5% experienced reduced rainfall, and 88% encountered prolonged drought conditions. These patterns are consistent with IPCC (2021) projections, which identify Southeast Asia as a climate hotspot facing early and severe impacts of global climate change. Coastal areas are experiencing more pronounced stressors, such as salinization (reported by 75% of households) and flooding (44.5%), which

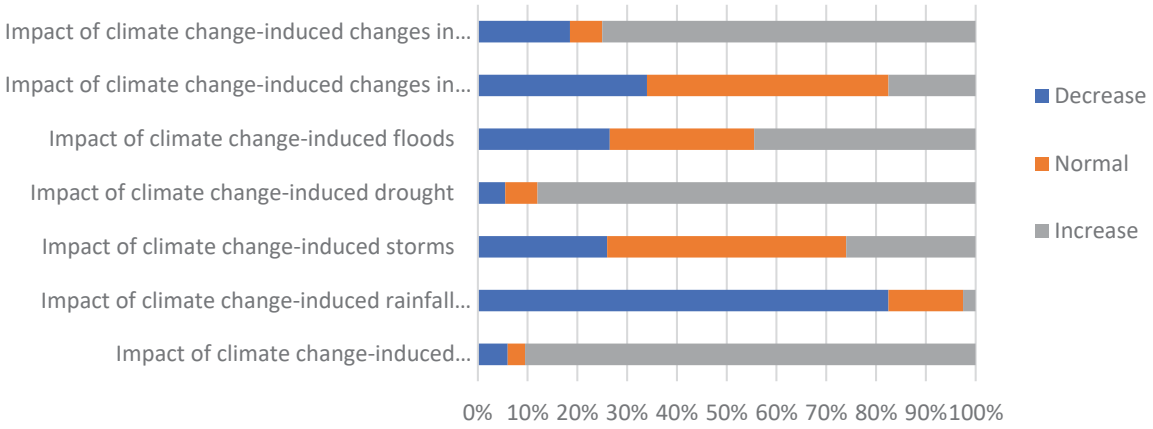

Fig. 4: Comparison of farming households' predictors of perceived climate change manifestations

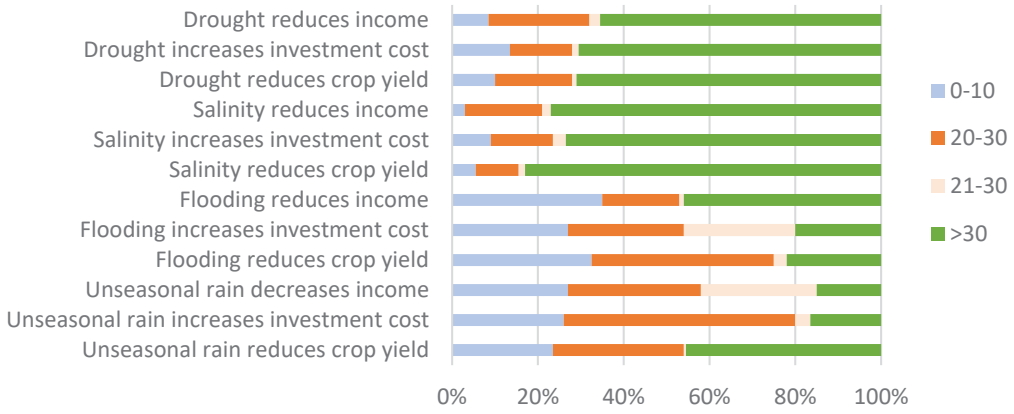

Fig. 5: Comparison of farming households' predictors of impacts of climate change on livelihoods

aligns with the research conducted by Smajgl *et al.,* (2015) on saline intrusion in the Mekong Delta.

Fig. 5 emphasizes the considerable socioeconomic consequences of climate change for farming households. Droughts have resulted in yield reductions for 71% of farmers, increased investment costs for 70.5%, and income losses for 65.5%. Likewise, salinization has caused a decline in yields for 83% of households, elevated production expenses, and lowered profits for over 70%. These findings support Nguyen *et al.,* (2024), who emphasized that climate change significantly exacerbates the vulnerability of agricultural livelihoods, particularly among small-scale farmers with limited adaptive capacity. Additionally, approximately 54% of households reported increased investment costs due to off-season rains, while 45.5% experienced reduced yields. These indirect consequences disturb farming timelines, destabilize agricultural markets, and compromise supply chains (Phuong *et al.,* 2024). Ultimately, the study reveals that climate change adversely affects agroecological conditions while simultaneously heightening uncertainties in economic and production realms. Addressing these challenges requires an integrated approach that enhances farmer awareness, improves agricultural infrastructure, and promotes strong financial and technical support mechanisms (Thornton *et al*., 2011; Bryan *et al.,* 2013).

The findings of the study reveal that deteriorating environmental factors, including the degradation of water, soil, and air quality, play a crucial role in

restricting agricultural productivity amid climate change. Farmers report serious impacts from degraded surface and groundwater, soil erosion, and reduced air quality. Extreme events including heatwaves, droughts, salinization, and floods further strain production. These changes have led to lower yields, higher costs, and falling incomes. Off-season rains also disrupt cropping and markets. The results underscore the fragility of small farmers and the importance of synchronized adaptation through enhanced awareness, upgraded infrastructure, and accessible support.

Model performance and significance of the multivariate logistic regression

Prior to conducting regression analysis, this study utilized Eq. 6 to assess the extent of multicollinearity among independent variables, with the objective of minimizing bias in regression coefficient estimates and standard errors, thereby enhancing model reliability and ensuring that the retained variables exhibit relatively high statistical independence. The two-stage VIF diagnostic results (Table 6) indicate that all VIF values remained within acceptable tolerance limits, with the majority falling below 5.0 and only a limited number of variables exceeding 7.0. The elimination of the variable "Flooding increases investment cost" (VIF > 15) substantially mitigated multicollinearity concerns. Overall, the final collection of variables adheres to the required standards for inclusion in the regression model, without causing

Table 6: VIF diagnostic results

Independent variables	Pre-screening VIF diagnostics	Post-screening VIF diagnostics	Independent variables	Pre-screening VIF diagnostics	Post-screening VIF diagnostics
1. YFE	2.60	2.60	17. Perceived impact of climate change on surface water quality	3.55	3.46
2. NCPY	4.63	4.56	18. Perceived impact of climate change on groundwater quality	4.10	3.87
3. CLA	1.33	1.33	19. Perceived impact of climate change on air quality	1.74	1.71
4. PCC	4.48	4.28	20. Perceived impact of climate change on cultivated soil quality	2.89	2.89
5. AMHI	2.70	2.68	21. Unseasonal rain reduces crop yield	7.78	7.69
6. Perceived water quality	2.64	2.63	22. Unseasonal rain increases investment cost	9.01	8.48
7. Perceived groundwater quality	2.45	2.45	23. Unseasonal rain decreases income	9.37	9.32
8. Perceived soil quality	2.21	2.21	24. Flooding reduces crop yield	5.47	3.97
9. Perceived air quality	2.22	2.16	25. Flooding increases investment cost	15.05	-
10. Impact of climate change-induced temperature variation	3.73	3.56	26. Flooding reduces income	12.76	5.74
11. Impact of climate change-induced rainfall variation	2.04	2.03	27. Salinity reduces crop yield	4.97	4.96
12. Impact of climate change-induced storms	4.05	3.82	28. Salinity increases investment cost	5.05	5.03
13. Impact of climate change-induced drought	7.25	7.05	29. Salinity reduces income	3.19	3.19
14. Impact of climate change-induced floods	2.75	2.75	30. Drought reduces crop yield	6.67	6.66
15. Impact of climate change-induced changes in river water levels	2.85	2.83	31. Drought increases investment cost	10.12	10.12
16. Impact of climate change-induced changes in salinity	3.59	3.36	32. Drought reduces income	4.92	4.91

Table 7: Assessing logistic regression model fit for climate change adaptation capacities

Adaptive_capacity	Chi-squared	df	P-level	Log Likelihood	AIC	Nagelkerke R-squared	AUC (%)	Percentage of correct classification (%)
CP	156.27	31	<0.001	−53.10	170.2	0.75	78	84.75
IPC	154.51	31	<0.001	−53.98	172	0.74	89	86.44
IL	156.11	31	<0.001	−55.00	174	0.74	84	88.33
LM	155.4	31	<0.001	−57.14	178.3	0.73	74	81.67
OA	151.55	31	<0.001	−59.07	182.1	0.72	82	88.33
CL	86.17	31	<0.001	−28.06	120.1	0.72	77	81.82
LT	96.35	31	<0.001	−36.74	137.5	0.7	78	78.72

significant bias related to collinearity problems.

The results from Table 7 reveal that adaptive strategies such CP, IPC, and IL are most strongly associated with household adaptive capacity. This is evidenced by high statistical indicators, including R^2 values above 0.74, AUC ranging from 78% to 89%, and correct classification rates exceeding 84%. These strategies reflect a proactive and flexible approach to climate change adaptation. In contrast, strategies such as LM, CL, LT, and OA remain statistically significant but exhibit lower explanatory power and predictive accuracy. Importantly, the shift in livelihoods reflects the least association, indicating that this choice is less available for numerous households because of significant resource demands and the risks involved. In summary, strategies that are driven by technical capabilities and utilize internal resources are likely to be more effective in boosting adaptive capacity in response to climate change. The ROC curve (Fig. 6) analysis reveals substantial heterogeneity in model discriminatory performance across the seven adaptation strategies, with AUC values ranging from 0.74 to 0.89, indicating a 15%-point variation in predictive accuracy. The IPC strategy exhibits the strongest discriminatory strength (AUC = 0.89), coming close to exceptional classification performance and implying that this adaptive behavior is guided by highly predictable patterns influenced by distinctly recognizable socioeconomic factors. IL and OA strategies exhibit good discriminatory performance with AUC values of 0.84 and 0.83, respectively, indicating that these strategies are governed by relatively systematic decision-making processes that can be effectively captured by the predictor variables. Conversely, the LM strategy exhibits the least level of discriminatory performance (AUC = 0.74), implying that migration decisions are affected by complex and varied factors that surpass the measured variables. This may include social networks, cultural aspects, and individual risk tolerance, which are challenging to quantify. CP, LT, and CL strategies demonstrate moderate discriminatory performance (AUC = 0.77-0.78), indicating intermediate levels of predictability. This variation in AUC values reflects the inherent complexity and heterogeneity of household adaptation decision-making processes. Strategies with higher AUC values likely represent more rational, resource-driven choices that respond predictably to measurable socioeconomic variables, while those with lower AUC values may involve more complex behavioral, cultural, or contextual factors that require additional explanatory variables or alternative modeling approaches to achieve improved predictive accuracy.

Factors influencing adaptive behavior adoption among farming households

The multivariate logistic regression analysis presented in Table 8 reveals that perception, particularly regarding climate change and its impacts on livelihoods, serves as a critical determinant of adaptive behavior among agricultural households. The result corresponds with prior research that underscores the significant role of farmer perceptions in shaping responses to climate adaptation (Khan *et al.*, 2021; Elum and Snijder, 2023). Among the independent variables examined, the perception of the ICCL emerges as a significant predictor, demonstrating a pronounced negative effect on most adaptive behaviors, with statistically robust odds ratios (OR) consistently below 1.0 and p-values less than 0.001 across multiple adaptation

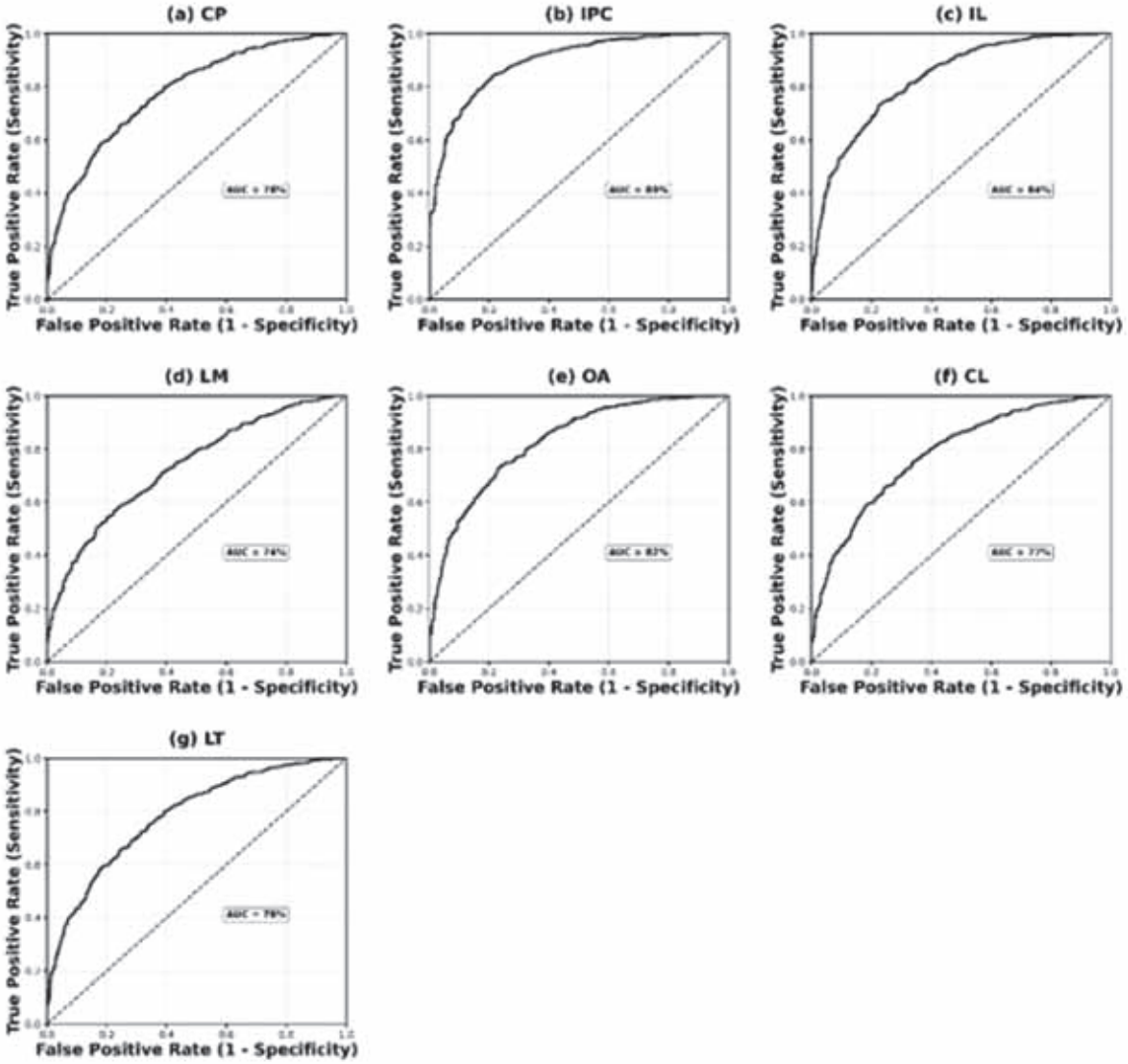

Fig. 6: ROC curves evaluating seven livelihood adaptation strategies to CC

strategies. Specifically, ICCL significantly reduces the probability of adopting adaptive practices, including CP (OR = 0.254; 95% CI: 0.14–0.46), LT (OR = 0.552; 95% CI: 0.298–1.022), and OA (OR = 0.321; 95% CI: 0.187–0.551). These results imply that families with an increased awareness of climate change effects show a stronger tendency to take proactive steps in altering their livelihood strategies, which is consistent with conclusions drawn from comparable studies in climate-sensitive areas (Sertse *et al.,* 2021; Wulansari *et al.,* 2021). Conversely, households with limited climate risk perception tend to maintain traditional production methods, exhibiting passive responses to climate change challenges (Khan *et al.,* 2022). PCCM variable exhibits a strong positive correlation with adaptive behaviors, serving as a significant driver of major behavioral changes, including CP (OR = 2.401; 95% CI: 1.406–4.099), LT (OR = 2.007; 95% CI: 1.07–3.762), and OA (OR = 2.222; 95% CI: 1.437–3.436). These conclusions emphasize that a clear and accurate awareness of global climate occurrences forms a vital groundwork for encouraging proactive adaptive strategies, thus improving the resilience of agricultural households (Mobeen *et al.,* 2025;

Table 8: Multivariate logistic regression analysis of factors impacting CC adaptation behaviors among farming households

Predictor variables	IPC	IL	CP	LT	CL	OA	LM
AMHI	1.108 (0.673, 1.823)	1.232 (0.745, 2.036)	1.115 (0.66, 1.882)	1.433 (0.782, 2.627)	1.214 (0.621, 2.374)	1.171 (0.697, 1.967)	1.182 (0.703, 1.988)
CLA	1.635*** (1.147, 2.33)	2.244*** (1.513, 3.329)	1.715*** (1.157, 2.542)	1.37 (0.905, 2.075)	1.396 (0.843, 2.313)	1.375* (0.974, 1.94)	1.374* (0.974, 1.936)
ICCL	0.367*** (0.213, 0.633)	0.334*** (0.191, 0.583)	0.254*** (0.14, 0.46)	0.552* (0.298, 1.022)	0.897 (0.401, 2.005)	0.321*** (0.187, 0.551)	0.315*** (0.183, 0.541)
NCPY	1.038 (0.561, 1.922)	1.186 (0.64, 2.199)	0.702 (0.364, 1.352)	0.489* (0.222, 1.078)	0.238*** (0.087, 0.648)	1.12 (0.612, 2.05)	1.133 (0.619, 2.076)
PCC	1.243 (0.719, 2.148)	1.237 (0.713, 2.147)	0.854 (0.479, 1.524)	1.017 (0.548, 1.89)	1.109 (0.465, 2.647)	1.06 (0.637, 1.764)	1.082 (0.65, 1.802)
PCCM	2.776*** (1.662, 4.637)	2.195*** (1.393, 3.458)	2.401*** (1.406, 4.099)	2.007** (1.07, 3.762)	1.071 (0.568, 2.022)	2.222*** (1.437, 3.436)	2.175*** (1.414, 3.346)
PICNR	0.865 (0.569, 1.316)	0.91 (0.599, 1.381)	0.695 (0.45, 1.074)	0.31*** (0.172, 0.558)	0.085*** (0.043, 0.167)	0.731 (0.485, 1.102)	0.729 (0.485, 1.096)
PRQS	0.796 (0.565, 1.12)	0.698** (0.49, 0.995)	0.766 (0.538, 1.09)	0.653** (0.444, 0.962)	0.706 (0.451, 1.106)	0.556*** (0.383, 0.806)	0.544*** (0.374, 0.791)
YFE	0.698 (0.396, 1.228)	0.712 (0.403, 1.258)	0.552** (0.311, 0.981)	0.976 (0.476, 2.003)	1.129 (0.446, 2.862)	0.639 (0.362, 1.129)	0.634 (0.358, 1.121)
N	200	200	200	200	200	200	200

***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses represent 95% confidence intervals.

Elum and Snijder, 2023). Beyond perceptual factors, structural variables such as CLA play a crucial role in adaptation decisions. The CLA variable significantly increases the probability of Income Livelihood (IL) (OR = 2.244; 95% CI: 1.513–3.329) and CP (OR = 1.715; 95% CI: 1.157–2.542), indicating that larger production scales enable households to allocate resources more flexibly and implement adaptive strategies more effectively (Elum and Snijder, 2023; Abid *et al.*, 2019). PRQS and PICNR significantly influence decisions related to CL and LT strategies. The PICNR variable demonstrates a pronounced negative association with LT (OR = 0.085; 95% CI: 0.043–0.167) and CL (OR = 0.31; 95% CI: 0.172–0.558), suggesting that households' recognition of climate-induced resource degradation serves as a key driver for shifting production practices to mitigate associated risks (Elum and Snijder, 2023; Sertse *et al.*, 2021). Variables including YFE, NCPY, PCC, and AMHI did not exhibit significant or consistent effects in explaining adaptive behaviors, with most odds ratios approximating 1.0 and p-values exceeding 0.05. These observations imply that without the influence of climate risk perception, neither farming experience nor household income can sufficiently drive behavioral change (Usman *et al.*, 2023; Mobeen *et al.*, 2025). The findings reveal that adaptation behaviors concerning climate change are not exclusively dictated by economic resources or agricultural experience; rather, they are significantly influenced by households' perceptions of climate change phenomena. This emphasizes the critical importance of enhancing climate communication, promoting community education, and delivering reliable climate information to build adaptive capacity at the household level, particularly in vulnerable rural areas (Usman *et al.*, 2023; Elum and Snijder, 2023; Khan *et al.*, 2021). While the results in Table 8 demonstrate that climate change perception strongly influences adaptation behavior (OR = 2.007-2.776), the cross-sectional design cannot exclude

Table 9: Marginal effects of binary logistic models

Explanatory variables	IPC	IL	CP	LT	CL	OA	LM
ICCL	-0.295	-0.291	-0.298	-0.204	-0.053	-0.305	-0.306
PCCM	0.212	0.201	0.179	0.095	-0.073	0.191	0.191
PICNR	-0.023	-0.033	-0.047	-0.296	-0.664	-0.041	-0.036
PRQS	-0.088	-0.089	-0.079	-0.107	-0.068	-0.075	-0.075
NCPY	0.062	0.04	-0.008	-0.132	-0.34	0.014	0.014
CLA	0.132	0.132	0.118	0.081	0.058	0.105	0.106
PCC	0.156	0.115	0.069	0.051	-0.073	0.088	0.088
AMHI	0.015	0.021	0.029	0.049	0.007	0.021	0.019
YFE	-0.055	-0.07	-0.067	-0.063	-0.067	-0.084	-0.084
N	200	200	200	200	200	200	200

reverse causality, whereby adaptation behavior shapes perception rather than vice versa. Farmers that have put resources into adaptation strategies may grow more responsive to climate data to support their choices, or they might gain increased awareness of climate risks as a result of the adaptation process itself. This potential reverse causality may explain the strong perception-behavior associations observed (R^2 = 0.70-0.75). Future longitudinal studies tracking the same farmers over time are needed to establish clear causal sequencing and validate these findings.

Marginal effects analysis of climate change adaptation strategy selection

Table 9 presents marginal effects from the multivariate logistic regression model, providing clear insights into how each explanatory variable influences the probability of adopting specific CC adaptation strategies. The coefficients reflect the alterations in probability that occur with a one-unit rise in each variable, while keeping the other variables unchanged. ICCL consistently demonstrated strong negative effects across all adaptive behaviors, with marginal effects ranging from -0.053 to -0.306. Specifically, values of -0.306 for LM and -0.305 for OA demonstrate that greater perceptions of the impact of climate on livelihoods significantly notably reduces the likelihood of opting for non-adaptive or passive responses. This finding aligns with Khan *et al*. (2021), which demonstrated the synergy between climate risk perception and adaptation responses among rice farming communities in Pakistan, and supports Abid *et al*. (2019) regarding farmers' perceptions and adaptation strategies to climate change. Conversely, PCCM exhibited positive effects on most adaptive behaviors, with relatively higher marginal effects observed for IPC (0.212), IL (0.201), CP (0.179), and OA (0.191). These findings indicate that acknowledging PCCM enhances the probability of implementing strategies that include IPC, IL, and CP. This conclusion is in agreement with the findings of Khan *et al*. (2022), which underscored the role of farmers' climate risk perceptions in their decisions regarding ICT-based agricultural information services. Furthermore, Mobeen *et al*. (2025) explored the perceptions of climate change and adaptation methods in irrigated agriculture in Punjab and Sindh, Pakistan. PICNR showed distinctly negative influences, particularly on LT (-0.296) and CL (-0.664). The substantial negative coefficient for CL suggests that households perceiving resource degradation due to CC are more likely to relocate farming sites as a coping strategy. This pattern reflects the findings of Sertse *et al*. (2021), which identified comparable adaptation strategies utilized by agricultural households in response to climate change risks in Ethiopia. Several additional factors demonstrated notable influences. CLA showed modest positive effects on the probability of adopting IPC (0.132), IL (0.132), CP (0.118), and LM (0.106). Households that possess larger tracts of land seem to have more leeway in resource allocation, making it easier to adjust production in reaction to climate variations (Wulansari *et al*., 2021). PCC also exhibited positive effects, albeit weaker in magnitude. AMHI and NCPY demonstrated minimal influence with very small coefficients, while YFE showed slight negative effects across most strategies, suggesting that more experienced farmers may be less inclined to change due to adherence to traditional practices (Usman *et al*., 2023). The insights gained from the marginal effects model emphasize the vital importance of perception in affecting the adaptation behaviors of farming households. ICCL emerged as a particularly strong determinant, whereas conventional socio-



Fig. 7: Adaptation strategy adoption comparison across saline, brackish, and freshwater ecological zones

economic factors such as income and farming experience showed relatively limited effects. The findings demonstrate that initiatives designed to improve awareness and providing precise, readily available information about climate risks are vital for fostering proactive adaptation among agricultural communities (Elum and Snijder, 2023).

Fig. 7 reveals distinct ecological zone differentiation in adaptation strategy adoption. The saline zone (An Nhon, An Quy, Giao Thanh) exhibited the highest rates with 95% LT and 88% CL adoption, while the brackish zone My Hung showed the lowest at 8% LT and nearly 0% CL. The freshwater zone Dai Dien demonstrated intermediate levels at 18% LT and 20% CL. These findings align with Khan *et al.* (2021) regarding climate risk perception and adaptation synergy. The immediate consequences of saltwater encroachment in saline regions elevate ICCL, fostering the adoption of transformation strategies. Conversely, Sertse *et al.* (2021) demonstrated PICNR's strong negative marginal effects on LT (-0.296) and CL (-0.664), explaining lower adaptation in complex brackish ecosystems. The remaining five strategies (IPC, IL, CP, OA, LM) achieved uniform 100% adoption across zones, indicating universality and minimal ecological dependence. According to Wulansari *et al.* (2021) and Usman *et al.* (2023), these strategies require no fundamental changes to traditional production systems. The findings suggest tailored awareness initiatives for each region, especially promoting the adoption of LT and CL in freshwater and brackish environments, as indicated by Elum and Snijder (2023).

RECOMMENDATION

To effectively promote climate change adaptation among smallholder farmers in the Mekong Delta, this study recommends that policymakers, agricultural extension services, and climate-related programs prioritize perception-based interventions. In particular, strategies ought to focus on increasing farmers' understanding of the effects of climate change and the risks to their livelihoods, as these factors were recognized as the most significant indicators of adaptive behavior in this study. Implementation should involve localized climate communication, participatory training, and context-specific information systems that translate abstract climate signals into actionable knowledge. It is essential to incorporate these efforts into the established agricultural advisory frameworks to promote accessibility and lasting effects. Psychological models such as protection motivation theory or theory of planned behavior can inform the design of communication strategies that trigger proactive responses. The study findings show that ICCL and PCCM significantly shape adaptation strategies, explaining up to 75% of behavioral variance. While ICCL functions as a risk-driven trigger, PCCM enables anticipatory actions.

Conversely, standard socioeconomic elements (for instance, income and experience) exhibit minimal explanatory strength. Thus, investing in perception-enhancing mechanisms addresses both cognitive and motivational foundations of adaptation. Such interventions are particularly crucial for resource-constrained households in climate-vulnerable zones. By incorporating behavioral insights into policy and practice, stakeholders have the ability to cultivate scalable, sustainable, and locally anchored resilience pathways in agriculture.

CONCLUSION

This study provides robust empirical support for both research hypotheses through multivariate logistic regression analysis of 200 agricultural households in Vietnam's Mekong Delta. Hypothesis 1 has been definitively validated, indicating that farmers who have a heightened awareness of climate change effects tend to implement proactive adaptation strategies, with PCCM exhibiting significant positive correlations (OR = 2.007 - 2.776, $p < 0.05$). Hypothesis 2 receives partial validation, as traditional socio-economic factors including farming experience (YFE), household income (AMHI), production costs (PCC), and cropping frequency (NCPY) showed minimal moderating effects (OR ≈ 1.0, $p > 0.05$), with only farm size (CLA) demonstrating significant moderation (OR = 1.7 2.2). Addressing the research questions, farmers' perceptions influence adaptation strategies through two distinct mechanisms. PCCM operates as a positive catalyst, with households recognizing climate manifestations being 2.0 to 2.8 times more likely to adopt change in production, increased labor input, and other adaptations. Alternatively, ICCL serves as a motivator influenced by risk, where an increased perception of livelihood threats significantly lessens passive reactions (OR = 0.254 - 0.367), driving households to pursue active adaptation measures. Regarding socio-economic moderation, the analysis reveals that traditional determinants (farming experience, household income, production costs, cropping frequency) have negligible influence on the perception adaptation relationship, challenging conventional assumptions about economic factors driving adaptation decisions. The only significant moderator identified was the area of cultivated land, suggesting that the availability of resources facilitates the conversion of climate perception into adaptive action. The study reveals farmers' perceptions operate through two pathways. PCCM serves as a positive catalyst with strong odds ratios (OR = 2.195 - 2.776) for production focused strategies, while ICCL acts as a risk driven motivator with significant negative associations (OR = 0.254 - 0.367) indicating higher perceived threats increase adaptation probability. This dual pathway model explains 70 to 75% of behavioral variance, demonstrating that psychological factors outweigh socio economic determinants and challenging conventional resource centric adaptation theories. The findings of the study support a significant change in climate adaptation policy, moving from a resource-oriented approach to one that is centered on perceptions, highlighting the importance of climate communication and improving risk awareness. For coastal delta regions globally, the research provides evidence-based guidance for developing adaptation programs prioritizing community education and farmer to farmer knowledge exchange. Nonetheless, the constraints involve a cross-sectional design, a focus on Vietnam's geographical context, self-reported perception metrics, and prioritizing adoption over the assessment of effectiveness. This study has some limitations. The use of simple random sampling within the five selected communes may introduce accessibility bias, favoring farmers who are easier to reach, as well as participation bias, since those willing to participate might systematically differ in their environmental awareness. Furthermore, relying solely on a structured 33 item questionnaire limits the ability to explore complex psychological processes due to the absence of qualitative methods. Moreover, the use of binary coding (0 and 1) for adaptation strategies could reduce the intricate and diverse characteristics of agricultural decision-making. Future research should include longitudinal studies tracking households over time, qualitative approaches exploring psychological processes, comparative regional analysis across different coastal systems, and effectiveness assessment using objective vulnerability measures. Evidence from empirical studies shows that perception is the main driver of climate adaptation behavior, forming the groundwork for the creation of behaviorally informed policies that emphasize the importance of climate communication and education in climate resilience strategies.

AUTHOR CONTRIBUTIONS

L.T. Hoa was responsible for the conception and design of the study, statistical analysis, data interpretation, manuscript drafting, supervision, and securing funding. N.T.T. Thuy contributed to data acquisition, statistical analysis, and data interpretation, and provided technical and material support. P.T. Duy was involved in critical revision of the manuscript, funding acquisition, and provided administrative and technical support.

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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.

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ABBREVIATIONS

%	Percent
°C	Degree Celsius
AIC	Akaike information criterion
AUC	Area under the curve
AMHI	Average monthly household income
CC	Climate change
CI	Confidence interval
CP	Change in production
CL	Change production location
CLA	Cultivated land area
FAO	Food and Agriculture Organization
FPR	False positive rates
IL	Increased labor input
IPC	Increased production cost
ICCL	Impacts of climate change on livelihoods
LL	Log-likelihood
LT	Livelihood transition
LM	Livelihood maintenance
m^2	Square meter
ME	Marginal effect
MLE	Maximum likelihood estimation

MONRE	Ministry of Natural Resources and Environment
NCPY	Number of crops per year
OA	Other adaptations
OR	Odds ratio
PCC	Production cost per crop
PCCM	Perception of climate change manifestations
PRQS	Perception of resource quality status
PICNR	Perception of the impacts of climate change on natural resources
ROC	Receiver operating characteristic
SE	Socio-economic
TPR	True positive rates
USD	United States Dollar
YFE	Years of farming experience
VIF	Variance Inflation Factor

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CASE STUDY

Eco-friendly plant nutrient management for chili growth, yield, and resistance in acidic soils

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ABSTRACT

BACKGROUND AND OBJECTIVES: The global demand for chili pepper (Capsicum annuum var. annuum) continues to grow due to increasing population pressures, changing dietary preferences, and the expansion of the food processing industry. This need is especially evident in regions that are dealing with limited land availability and challenges related to soil fertility. In order to sustain productivity, a significant number of farmers have come to depend heavily on chemical fertilizers. However, the prolonged and excessive use of synthetic inputs has led to adverse environmental consequences, including soil nutrient imbalance, degradation of soil microbial communities, water contamination, and the accumulation of chemical residues in crops, posing risks to both ecosystems and human health. In light of these concerns, this study sought to evaluate the efficacy of Integrated Plant Nutrient Management, a comprehensive strategy that merges inorganic fertilizers in improving the growth, yield, and resilience of the chili pepper cultivar 'Kencana'.

METHODS: The experiment was conducted at the Indonesian Vegetable Research Institute in Lembang, West Java. A split-plot design in a randomized complete block arrangement with three replications was employed. The main plots were designated for six organic fertilizer treatments, comprising chicken manure and bamboo rhizosphere soil. Four combinations of inorganic fertilizers comprising nitrogen, phosphorus, potassium, and Starter Solution Technology were applied in the subplots.

FINDINGS: The results indicated that the integrated application of chicken manure, bamboo rhizosphere soil, Starter Solution Technology, and nitrogen, phosphorus, and potassium fertilizers significantly enhanced plant growth parameters, increased biomass by 15–20 percent compared to inorganic fertilizer alone, and improved overall plant vigor. The main plots were designated for six organic fertilizer treatments, comprising chicken manure and bamboo rhizosphere soil. Furthermore, the Integrated Plant Nutrient Management approach reduced the incidence of pest and disease attacks, suggesting improved plant resistance and healthier agroecosystem dynamics.

CONCLUSION: The study highlights that Integrated Plant Nutrient Management serves as a practical and eco-friendly method for boosting chili pepper production and lowering ecological risks. By combining locally available organic inputs with targeted inorganic fertilizers, Integrated Plant Nutrient Management promotes a more balanced nutrient supply, enhances soil health, and builds crop resilience, supporting the transition toward environmentally responsible and economically viable chili production system.

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INTRODUCTION

Chili peppers (*Capsicum annuum variety annuum*) are a crucial global commodity, recognized for their medicinal and culinary applications. s the global population is anticipated to hit 9.7 billion by 2050, the demand for crops rich in nutrients, including chili peppers, is projected to grow considerably (Olatunji and Afolayan, 2018; Tripathi *et al*., 2018). To meet this demand, many farmers rely heavily on chemical fertilizers to boost yield. Nonetheless, the overuse and extended application of synthetic inputs have resulted in significant environmental problems, such as soil degradation, diminished biodiversity, water contamination, and the buildup of chemical residues in agricultural products (Liang *et al*., 2020; Hossain *et al*., 2022). Globally, an estimated 33 percent (%) of soils are degraded, resulting in the annual loss of nearly 100 million hectares (ha) of productive land (UNCCD, 2023). In reaction, nations including Indonesia have adopted policies aimed at promoting sustainable land use (Kenji, 2018). This emphasizes the pressing requirement for eco-friendly nutrient management strategies that enhance agricultural productivity while safeguarding soil health and environmental quality (Batabyal, 2017; Khurshid *et al*., 2021; Paramesh *et al*., 2023;Gerona-Daga *et al.,* 2024; Bakar *et al.,* 2024). Integrated plant nutrient management (IPNM) is a promising strategy that combines organic fertilizers (OF) and inorganic fertilizers (IF) to optimize nutrient availability, enhance soil microbial activity, and improve crop resilience (Rahman *et al*., 2021; Paramesh *et al*., 2023; Ye *et al*., 2018). Sustainable agricultural success relies on a balanced nutrient supply, which can be achieved through IPNM. The harmonious mixture of these fertilizers enables quicker nutrient transformation processes, thereby increasing soil microbial activity (Hu *et al*., 2018). OF, such as animal manure and decomposable materials has been shown to improve chili productivity and fruit quality by 44% (Valenzuela-García *et al*., 2019), while, the combination of OF and IF, particularly those derived from animal manure and decomposable materials, not only enhances soil quality but also suppressing pests and diseases (Yu *et al*., 2024). The application of bio-fertilizers also aids in sustainable production through the enhancement of nutrient mobilization and overall plant health (Liu *et al*., 2024). Studies report that IPNM can increase crop yields by 8% to 150%, depending on the management system (Samanta and Sengupta, 2024; Soni and Nachiketa, 2023; Magar *et al*., 2023), and by 1.3% to 66.5% depending on the cropping system (Paramesh *et al*., 2023). Establishing the most effective fertilizer combination is key to maximizing chili pepper productivity and advancing sustainable agricultural practices. As an innovative strategy in modern farming, integrating OF and IF addresses global challenges such as the rising demand for food, environmental instability, and the detrimental effects of excessive chemical fertilizer use. The detrimental consequences, including environmental pollution, reduced soil health, and the degradation of ecosystems, emphasize the need for balanced nutrient management practices to secure the long-term viability of agricultural systems. Based on economic evaluations in other studies, integrating OF inputs (e.g., CM, compost, biofertilizers) with reduced chemical IF use can lower input costs while increasing yield and profit margins (Altaf *et al*., 2019). Despite these promising findings, empirical research on the optimal OF-IF combinations for chili pepper cultivation, especially under tropical agroecological conditions such as those in Indonesia, remains limited. Moreover, current studies have mainly emphasized yield outcomes, with insufficient focus on the broader implications of IPNM regarding pest and disease management, soil health, and long-term sustainability. This gap limits the practical application of IPNM as a holistic approach to sustainable chili production amid increasing food demand and environmental decline. This study hypothesizes that the integrated application of OF using chicken manure (CM) and bamboo rhizosphere soil (BRS) with IF containing nitrogen-phosphorus-potassium (NPK) and Starter Solution Technology (SST) will significantly improve growth, yield, and resistance to pests and diseases compared to IF alone in chili pepper cultivar (cv.) 'Kencana'. The study aims to examine the effects of IPNM, which combines OF and IF, on the growth, pest and disease suppression, and yield performance of chili pepper cv. 'Kencana'. The study was conducted in Lembang, West Java, Indonesia, from 2022 to 2023.

MATERIALS AND METHODS

Climatic conditions in the location study

The field study was carried out at the Indonesian Vegetables Research Institute (IVEGRI), located at

Table 1: Initial fertility status of the soil samples, and some chemical characteristics of the Andosol soil

Chemical characteristics			Analysis values	Criteria
Potential hydrogen-water (pH-H_2O)			5.20	Acid
Potential hydrogen-potasium chloride (pH-KCl)			4.50	Acid
Carbon(C)-organic (%)			6.69	Very high
Nitrogen (N)-total (%)			0.39	Low
Carbon-nitrogen (C/N) ratio			9.0	Low
diphosphorus pentoxide (P_2O_5)– Bray 1 (mg/kg)			25.57	Low
Potassium (K) – Morgan (mg/kg)			123.5	Medium
Calcium (Ca) (cmol(+)/kg)			14.70	Medium
Magnesium (Mg) (cmol(+)/kg)			2.37	Low
Maturity stage	Soluble solids	Acidity	Soluble solids/acidity	pH
	°Brix	g/100 mL		
Green	4.86[a]	0.67[a]	7.44[a]	2.81[a]
Color break	7.27[b]	1.00[b]	7.49[a]	2.93[a]
Yellow	8.31[b]	0.95[ab]	8.89[a]	2.99[a]
Orange	11.80[c]	0.28[c]	49.08[b]	3.51[b]

1,250 meters (m) above sea level, at latitude 6°48'S and longitude 107°39'E in Lembang, West Java, Indonesia. According to the site location study, humidity fluctuates from 34% to 90%, with an average annual temperature of around 20 degrees Celsius (°C) and precipitation levels reaching approximately 1,900 millimeters (mm), respectively. The soil type was Andosol, with an average potential hydrogen (pH) ranging from 5.0 to 6.0 (Table 1).

Field trial

In a fully randomized complete block design, three replications were implemented using a split-plot layout. Randomization was performed manually during plot assignment using random number tables. OF, such as CM, were used in the main plots in combination with the following treatments: (a1) humic acid (HA); (a2) mycorhiza-compost (MC); (a3) microbia from fermented BRS; (a4) Glio-compost (GC); (a5) seaweed extract (SW); and (a6) CM alone. All OFs were applied a week prior to transplanting. Four subplot treatments were used to apply the IF SST + NPK based on nutrient levels (SST + NPK): (b1) SST + NPK 1000 kilogram per hectare (kg/ha), (b2) SST + NPK 500 kg/ha, (b3) SST + NPK based on nutritional status (BNS) (654 kg/ha), and (b4) NPK 1,000 kg/ha as a control treatment. To reduce damage from pests and diseases, the chili seedlings cv. 'Kencana' was cultivated in a protected nursery. The seeds were deposited in a nursery with a screen before being placed in warm water at 50 °C for 20 minutes (min). Seedlings were moved into experimental beds with reflective plastic mulch five weeks after they were sown. Manual preparation of the land began with plowing and setting up beds with a distance of 50 x 70 centimeters (cm). The distance between blocks and plots was 1 m and 0.5 m, respectively. The total area of the experimental plots was 3,000 square meters (m^2) (100 plants per plot). Before transplanting, 20 tons per hectare (t/ha) of CM (Susilawati *et al*., 2023), an OF, was applied as a control and 15 t/ha as a treatment (Costa *et al*., 2015). The fertilizers were applied and mixed with the soil along the planting lanes. Biofertilizers such as HA, SW, and BRS were applied to the soil at a rate of 10 Liters per hectare (L/ha). At 20 kg/ha, MC and GC were applied. The initial half of the recommended quantity of NPK fertilizer was utilized before planting, and beginning one month post-planting, the second half was applied as a solution every ten days. The preparation of SST involved dissolving 22 grams (g) of NPK (15:15:15) and 51 g of ammonium sulfate (containing 21% N and 24% sulfur (S) in 10 L of water. SST solution was applied at 50 milliliters (mL) per plant, followed by approximately 170 mL of water 30 min later. SSTs were applied at 0, 10, and 35 days after planting (DAP).

Parameter observation

Ten randomly selected plants per plot were monitored weekly, beginning 30 DAP, to assess agronomic parameters. Measurements included plant height, canopy width, and other growth-related traits. Pest damage and the occurrence of diseases were

assessed on a weekly basis by observing symptoms on both plants and fruits, taking into account the degree and intensity of the damage. At harvest, fruit yield per plot was recorded and extrapolated to estimate average yield per hectare. Furthermore, the morphological traits of the fruit, including weight, length, and diameter, were recorded during each harvest.

Data analysis

Data was analyzed using Statistical Analysis System (SAS) software 9.4. Least Significant Difference (LSD) was used to compare means at a probability (P) ≤ 5% significance level in a two-way analysis of variance (ANOVA) to assess parameter fluctuations. Before executing ANOVA, the assessment of statistical assumptions was specifically performed by testing for the normality of residuals using Levene's test.

RESULTS AND DISCUSSION

Soil characteristics

The soil is acidic, both in water and in potassium chloride (KCl), which can limit nutrient availability for plants. A high concentration of organic C indicates a considerable amount of organic matter, which contributes positively to soil structure and its capacity to hold water. Despite this, total nitrogen is low, and the carbon-nitrogen (C/N) ratio is also low (ideal is ~10–12), indicating limited nitrogen mineralization and availability for plant uptake. Phosphorus (P) is low, potentially limiting root development and flowering. Potassium (K) and calcium (Ca) levels are moderate, offering moderate support for plant metabolism and cell wall integrity. A lack of magnesium (Mg) may hinder the formation of chlorophyll and the effectiveness of photosynthesis (Table 1). Due to its abundant organic matter, the soil shows promise, but it necessitates amendments to tackle acidity and to add N, P, and Mg for improved fertility and productivity.

Plant growth

The combination of OF, such as CM, with IF (SST + NPK) significantly improved plant height, canopy width, leaf area, number of branches, root length, root weight, and biomass accumulation. Applying small amounts of liquid fertilizer (starter solution) immediately after transplanting significantly enhanced both early growth and overall yields across various vegetables, including cabbage, cherry tomato, sweet pepper, and chili pepper. Furthermore, this approach facilitated a more efficient release of nutrients from organic composts (Ma and Kalb, 2006).

Plant height and canopy width

The combination of CM with BRS and SST + NPK treatments significantly enhanced plant height and canopy width compared to control treatments. For instance, plants treated with CM + BRS exhibited an average height of 97.30 cm and a canopy width of 72.78 cm, indicating improved nutrient uptake and enhanced photosynthetic efficiency (Table 2). The combined influence of BRS on fostering beneficial microbial activity resulted in enhanced soil health and nutrient availability, which is vital for optimal plant growth.

Leaf area and number of branches

Table 2: Effect of OF, IF, and their interaction (OF x IF) treatments on plant height (cm) and canopy width (cm)

OF	IF									
	Plant height (cm)					Canopy width (cm)				
	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)
CM + BRS	97.30	97.20	98.19	95.24	96.98	72.78	72.21	72.57	70.65	72.05
CM + MC	96.71	96.62	97.61	94.66	96.40	70.93	70.36	70.72	68.81	70.20*
CM + GC	96.13	96.04	97.03	94.08	95.82	72.20	71.63	71.99	70.07	71.47
CM + HA	97.75	97.65	98.64	95.69	97.43	72.36	71.79	72.15	70.24	71.63
CM + SW	98.15	98.05	99.04	96.09	97.83	72.95	72.38	72.74	70.82	72.22
CM	95.24	95.15	96.14	93.19	94.93*	71.35	70.78	71.14	69.23	70.62*
Mean (IF)	96.88	96.79	97.78	94.83*		72.093	71.52	71.88	69.97*	
	(OF) = 1.05; (IF) = 0.84 ; (OF X IF) = 2.52					(OF) = 1.12; (IF) = 0.96 ; (OF X IF) = 2.88				

SST=starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed. The numbers in the columns and the rows followed by the * are significantly different according to the LSD (P< 0.05).

Table 3: Effect of OF, IF, and their interaction (OF x IF) treatments on Leaf area and no. of branching

OF	IF									
	Leaf area					No. of branching				
	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ ha	Mean (OF)	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)
CM + BRS	10170.43	10096.76	10381.75	9807.78	10114.18	12.69	12.53	12.72	12.36	12.57
CM + MC	9519.51	9234.52	9308.18	8945.54	9251.94	12.31	12.11	12.28	11.94	12.16
CM + GC	9202.79	8917.81	8991.47	8628.83	8935.22*	12.18	11.99	12.15	11.82	12.03
CM + HA	10144.10	9859.12	9932.79	9570.14	9876.54	12.68	12.49	12.65	12.32	12.53
CM + SW	10262.23	9977.24	10050.91	9688.26	9994.66	12.47	12.28	12.44	12.11	12.32
CM	10022.43	9737.45	9811.11	9448.47	9754.87	12.27	12.07	12.24	11.90	12.12
Mean (IF)	9922.13	9637.14	9710.81	9348.17*		12.44	12.24	12.41	12.08	
	(OF) = 0.81; (IF) = 1.50 ; (OF X IF) = 2.54					(OF) = 1.03 (IF) = 1.29; (OF X IF) =2.92				

SST starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed. The numbers in the columns and the rows followed by the * are significantly different according to the LSD (P< 0.05).

The integration of CM with BRS resulted in the highest leaf area (10,381.75 cm^2) and branching (12.72 per branch) (Table 3), indicating enhanced photosynthetic efficiency and plant vigor. Studies on cocoa seedlings indicated that the combination of liquid OF and diminished NPK rates greatly boosted growth metrics. A 25% reduction in NPK combined with Licuid OF led to gains of 45–95% across various parameters such as stem diameter and leaf area (Hartawan *et al.,* 2024).

Root length and root weight

Plants treated with CM and microbial inoculum exhibited the longest root length at 30.69 cm and the heaviest root weight at 49.80 g (Table 4). This underscores the critical role of nutrient-rich conditions in developing vigorous root systems for optimal water and nutrient absorption. A study on chrysanthemum demonstrated that liquid OF substantially improved root systems by 10–77% compared to NPK-only controls, and boosted above-ground growth by 11–33%. Enhanced nutrient availability and microbial activity were key contributors to these gains (Ji *et al.,* 2017).

Fresh and dry weight biomass

The highest fresh weight (1,383.99 g) and dry weight (224.21 g) were observed in treatments with CM and HA, while CM + SW extract showed lower values (Table 5). This emphasizes the significance of particular organic amendments in boosting biomass production. The integration of OF and IF effectively enhances plant growth and overall health, driven by synergistic interactions that improve nutrient availability, microbial activity, and soil structure. This combination fosters efficient resource use, which is crucial for maintaining agricultural sustainability in the future (Parani and Nanthini, 2021; Ahmed *et al*., 2021). Additionally, SST + NPK fertilizers provide immediate nutrient availability, accelerating plant growth and yield optimization. These observations point out the critical role of adopting balanced fertilization methods to boost productivity and mitigate environmental consequences. The combination of organic matter (CM and BRS) with inorganic nutrients may create a more favorable and resource-diverse environment for microbial colonization, supporting oligotrophic taxa, thereby enhancing microbial diversity. In addition, under IPNM treatments, enhanced enzymatic activity will affect greater microbial metabolic activity, better organic matter decomposition, and improved nitrogen and phosphorus mineralization, which directly supports plant nutrient uptake. Furthermore, it was noted that the combined application of OF and IF supports plant development and enhances soil health, contributing significantly to sustainable agricultural practices (Gangadhar *et al.,* 2020).

The synergy between BRS and NPK-based nutrient status demonstrates lower pest

Table 4: Effect of OF, IF, and their interaction (OF x IF) treatments on Root length (cm) and Root weight (g)

OF	IF									
	Root length (cm)					Root weight (g)				
	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ ha	Mean (OF)	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)
CM + BRS	30.69	29.46	28.79	30.43	29.84	47.80	45.80	45.39	44.36	47.34
CM + MC	30.58	29.35	28.69	30.33	29.74	49.01	47.0	44.61	45.58	46.56
CM + GC	30.38	29.15	28.49	30.13	29.54	48.76	46.77	44.36	45.33	46.31
CM + HA	29.92	28.69	28.02	29.66	29.07	49.22	47.22	44.81	45.79	46.76
CM + SW	27.14	25.92	25.25	26.89	26.30*	43.13	41.14	38.73	39.70	40.67*
CM	28.87	27.65	26.98	28.62	28.03	47.69	45.70	43.28	44.26	45.20
Mean (IF)	29.60	28.37	27.70*	29.34		47.60	45.60	43.20*	44.17	
(OF) = 1.03; (IF) = 0.79 ; (OF X IF) = 2.84						(OF) = 1.21 (IF) = 1.44; (OF X IF) =2.93				

SST=starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed. The numbers in the columns and the rows followed by the * are significantly different according to the LSD (P< 0.05).

Table 5. Effect of OF, IF, and their interaction (OF x IF) treatments on total wet matter (g) and total dry matter (g)

OF	IF									
	Total wet matter (g)					Total dry matter (g)				
	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ ha	Mean (OF)	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (IF)
CM+ BRS	1289.68	1372.35	1315.13	1323.76	1325.22	199.15	211.92	200.82	202.98	203.72
CM + MC	1216.39	1299.079	1241.86	1250.486	1251.95	193.82	206.58	195.49	197.65	198.38
CM + GC	1297.59	1380.28	1323.06	1331.69	1333.15	203.66	216.42	205.33	207.49	208.23
CM + HA	1301.30	1383.99	1326.78	1335.401	1336.87	211.45	224.21	213.11	215.28	216.01
CM + SW	1123.62	1206.32	1149.09	1157.722	1159.19*	178.67	191.44	180.34	182.50	183.24*
CM	1283.01	1365.71	1308.48	1317.112	1318.58	208.63	221.39	210.30	212.46	213.19
Mean (IF)	1251.92*	1334.62	1277.40	1286.028		199.23*	211.99	200.89	203.06	
(OF) = 0.81; (IF) = 1.50 ; (OF X IF) = 2.54						(OF) = 1.03 (IF) = 1.44; (OF X IF) =2.83				

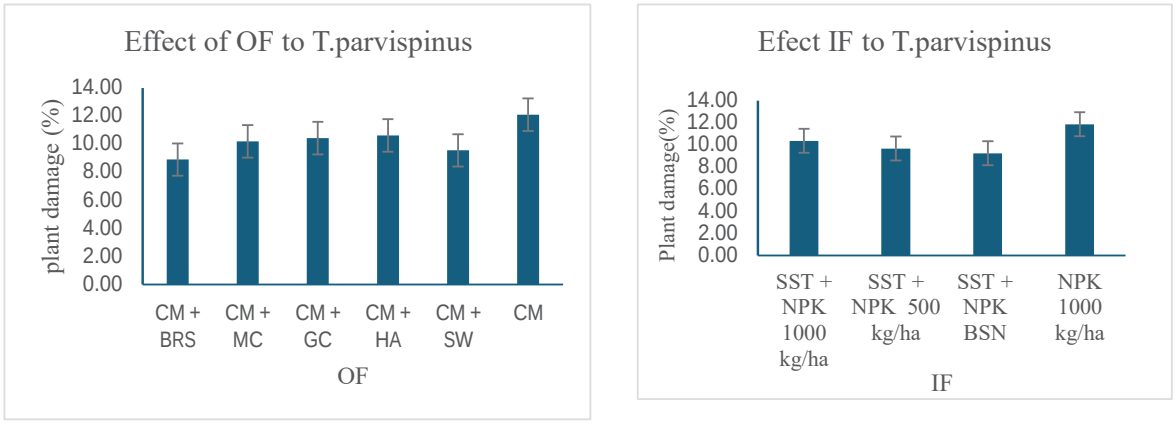
SST= starter solution technology; BSN=NPK based on nutrition; CM=chicken manur e; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed.The numbers in the columns and the rows followed by the * are significantly different according to the LSD (P< 0.05).

infestations, suggesting that BRS exhibits natural pest-suppressive properties (Delai *et al*., 2024). Additionally, beneficial microbes from BRS stimulate plant defense mechanisms, creating a biological shield against pest populations (Huang *et al*., 2025). Studies demonstrate the efficacy of Beauveria bassiana and Verticillium lecanii in the control of thrips and mites, highlighting the significance of microbial inoculants for sustainable pest management.

Effect of integrated plant nutrient management on pests and diseases

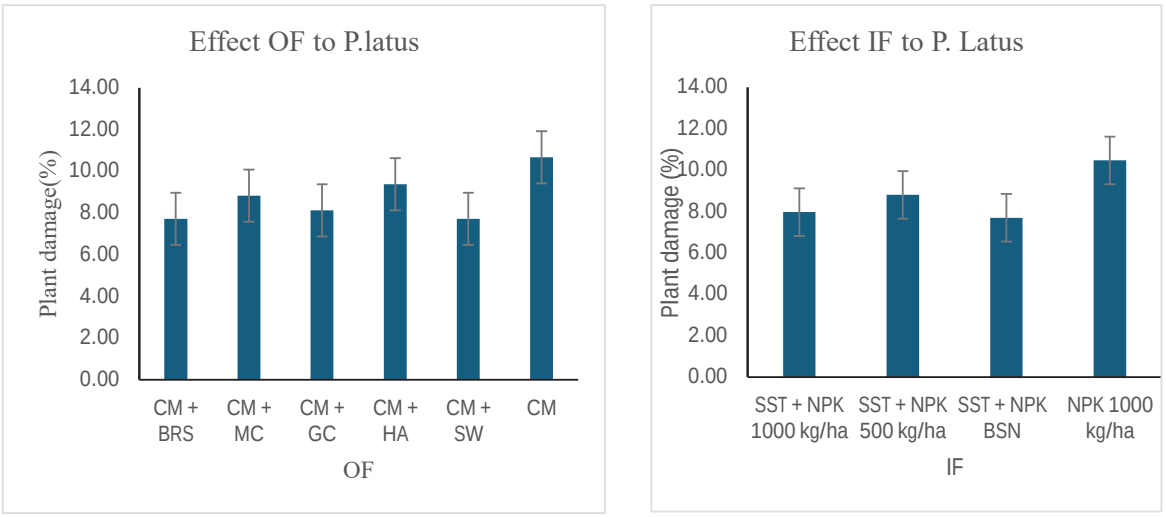
Pest incidence

The occurrence of pests in chili peppers, influenced by different types of OF and IF, is illustrated through four primary pests, specifically thrips, Thrips parvispinus (Fig. 1), and mites, Polyphagotarsonemus latus (Fig. 2), that appear during the vegetative phase, while Helicoverpa armigera (Fig. 3) and Bactrocera sp. (Fig. 4) emerge during the reproductive phase. The



A B

Fig. 1: A. Damage to chili plants caused by *T. parvispinus* infestation in OF, B. Damage to chili plants caused by *T. parvispinus* infestation in IF.
(The horizontal axis is denoted for OF=organic fertilizer; IF=inorganic fertilizer; SST=starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed)



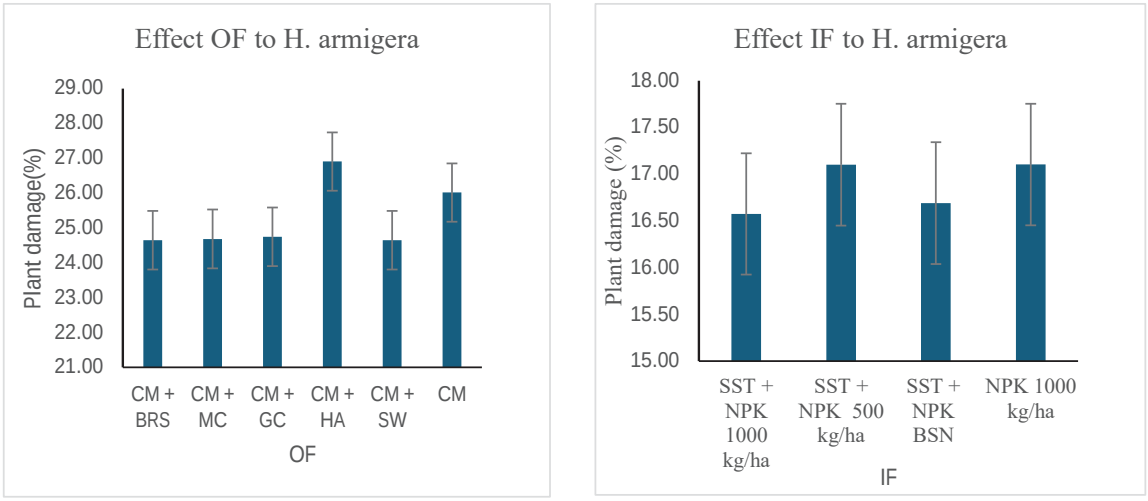
A B

Fig. 2: A. Damage to chili plants caused by *P. latus* infestation in OF, B. Damage to chili plants caused by *P. latus* infestation in IF.
(The horizontal axis is denoted for OF=organic fertilizer; IF=inorganic fertilizer; SST=starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed)

results showed that treatments incorporating SST + NPK, based on nutrient status, significantly reduced pest populations, particularly Thrips parvispinus and Helicoverpa armigera. Plants receiving CM + BRS exhibited lower pest damage levels compared to those treated with CM alone. According to Alyokhin *et al*. (2019), this reduction is likely due to increased plant vitality and health stemming from a well-balanced nutrient supply, rendering plants less vulnerable to pest invasions.

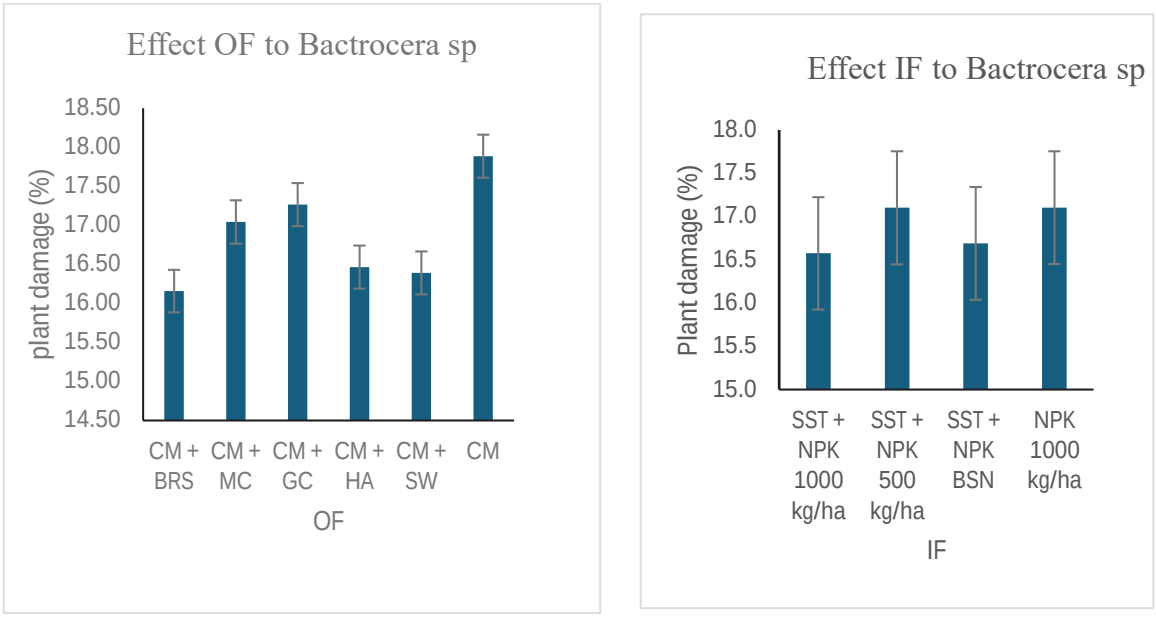
Disease suppression

The integration of BRS with OF and IF enhances plant immunity against major pathogens such as



A B

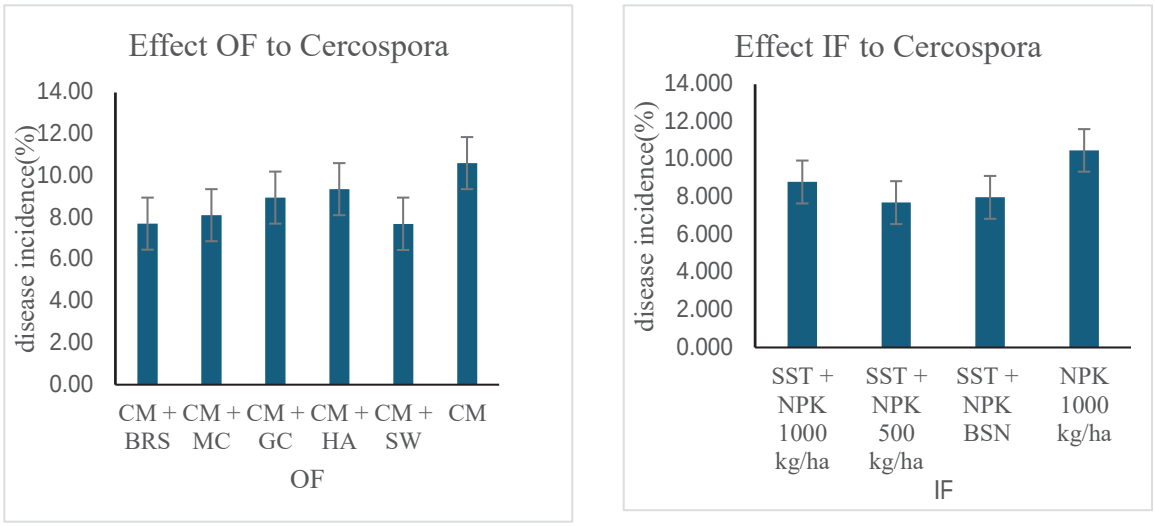
Fig. 3: A. Damage to chili fruits caused by *H. armigera* infestation in OF, B. Damage to chili fruits caused by *H. armigera* infestation in IF. (The horizontal axis is denoted for OF=organic fertilizer; IF=inorganic fertilizer; SST=starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed)



A B

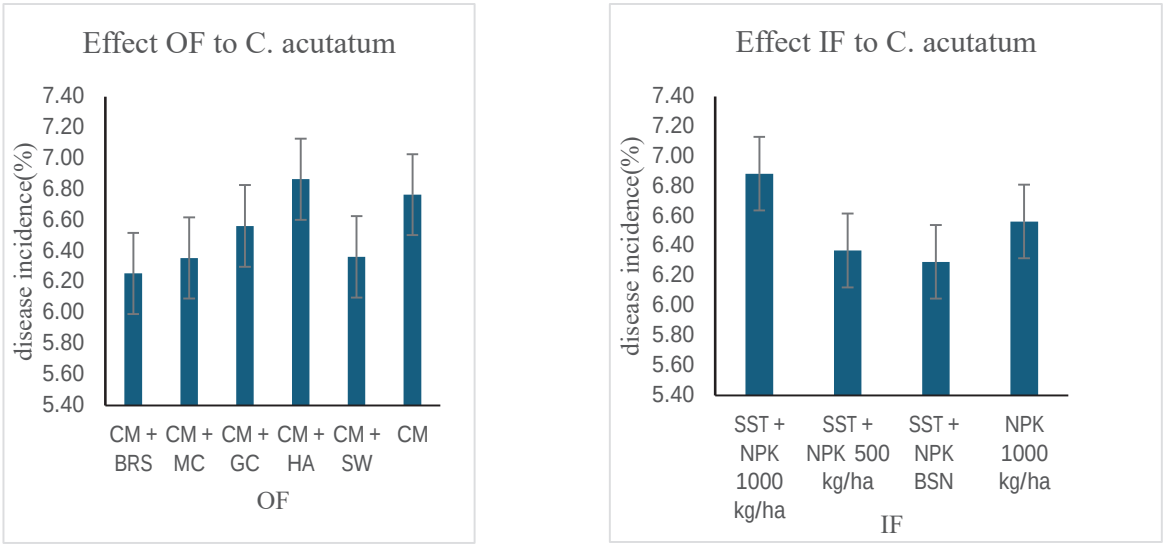
Fig. 4: Damage to chili fruits caused by *Bactrocera sp.* infestation in OF, B. Damage to chili fruits caused by *Bactrocera sp.* infestation in IF. (The horizontal axis is denoted for OF=organic fertilizer; IF=inorganic fertilizer; SST starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed)

Cercospora sp. (Fig. 5) and Colletotrichum acutatum (Fig. 6). The diminished frequency of pests and diseases associated with IPNM is due to multiple interrelated biological, chemical, and ecological factors that bolster plant resistance and reduce pathogen activity. Beneficial microbes present in BRS strengthen systemic resistance, thereby reducing disease incidence. These results are consistent with



A B

Fig. 5: A. Damage to chili plants caused by *Cercospora* sp. infestation in OF, B. Damage to chili plants caused by *Cercospora* sp. infestation in IF.
(The horizontal axis is denoted for OF=organic fertilizer; IF=inorganic fertilizer; SST=starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed)



A B

Fig. 6: A. Damage to chili fruits caused by *Colletotrichum acutatum* infestation in OF, B. Damage to chili fruits caused by *Colletotrichum acutatum* infestation in IF.
(The horizontal axis is denoted for OF=organic fertilizer; IF=inorganic fertilizer;SST=starter solution technology; BSN=NPK based on nutrition; CM=chicken manure; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed)

earlier studies that emphasize the importance of microbial inoculants in sustainable pest and disease management (Sharma *et al*., 2024; Díaz-Rodríguez *et al*., 2025). Antagonistic fungi, including Trichoderma spp. and Penicillium spp., exhibited strong biocontrol activity, significantly reducing disease occurrence while promoting root health. Furthermore, the use of SW extracts improved the microbial community in the rhizosphere, boosting nutrient absorption and stimulating plant defense responses (Ali *et al*., 2021). Mohammed and Khalid (2022) and Yugvinder *et al*. (2021) reported that combining SW extracts with fungicides effectively controls Alternaria sp. infections, thus minimizing pathogen spread in chili cultivation. Beneficial microbial communities and both OF and IF work together to enhance crop resilience, boost plant immunity, and increase soil fertility (Kumar *et al*., 2019). This cohesive strategy promotes a sustainable agricultural framework and lessens dependence on synthetic pesticides (Latifah *et al*., 2019; Tian *et al*., 2024). The study underscores the critical role of balanced fertilization practices for improving resistance to diseases and controlling insects. Farmers can improve crop yield, lower chemical inputs, and promote plant health through integrated plant nutrition management (Bhat *et al*., 2022; Sharma *et al*., 2024). Acidic soil environments (pH < 5.5) can significantly impact plant health and pest interactions by affecting root physiology, nutrient availability, and soil microbial communities. Under low pH conditions, the solubility of toxic elements like aluminum (Al^{3+}) and manganese (Mn^{2+}) increases, damaging root development and reducing the uptake of essential nutrients such as nitrogen, phosphorus, and calcium. This nutrient shortfall reduces the vitality of plants and interferes with their inherent defense systems, rendering crops more exposed to pests and pathogens. Additionally, acidification can suppress beneficial rhizosphere organisms, including biocontrol agents and symbiotic fungi, while promoting certain soil-borne pathogens, which shifts the ecological balance toward conditions that favor disease. Additionally, acidic soils serve to amplify stress, intensifying biological and environmental challenges in agroecosystems, which emphasizes the necessity for pH management in strategies for integrated pest and disease control. Regulating soil pH is crucial for microbiome-driven disease management in sustainable crop systems (Li *et al*., 2017; Thakur *et al*., 2022).

The reduced incidence of pests and diseases under IPNM is not the result of a single factor, but rather a synergistic interaction of improved nutrition, enhanced microbial activity, induced plant defenses, and ecological suppression of pathogens. These mechanisms are essential for enhancing the health and resilience of agroecosystems, which in turn supports sustainable chili cultivation.

Effect of OF and IF on yield parameters and attributes of chili pepper

The results show that the yield variables of chili, including flower and fruit output, fruit size, weight, and total yield per hectare, are affected by OF and IF. The findings illustrate the substantial impact of nutrition management greatly influences chili production.

Number of flowers and fruit production

The application of OF and IF (SST + NPK) demonstrated significant differences in flower and fruit production. The combination of CM with BRS resulted in the highest averages, producing 159.65 flowers and 203.80 fruits per plant. Similarly, CM with GC yielded 151.19 flowers and 181.97 fruit per plant (Table 6). In contrast, SST + NPK at 1,000 kg/ha produced lower flower and fruit counts, reinforcing the benefits of organic amendments in enhancing soil microbial activity and nutrient availability (Gangadhar *et al*., 2020).

Fruit size and diameter

The integration of CM with BRS resulted in an average fruit length of 16.89 cm, consistent across various inorganic treatments. Other combinations, including CM with MC and GC, showed similar lengths, averaging 6.81 to 16.88 cm. The highest fruit diameter was observed in CM-based treatments, maintaining a mean of 0.86 to 0.87 cm, with no significant differences between organic and inorganic treatments (Table 7). The growth in fruit length can be linked to the improved generation of leaves, which in turn enhances photosynthetic efficiency. This leads to a higher synthesis of carbohydrates, ensuring effective translocation from source tissues (leaves) to sink organs (reproductive structures). Consequently, the increased availability of assimilates facilitates fruit elongation, enhancing growth and development

Table 6: Effect of OF, IF, and their interaction (OF x IF) treatments on Number of flowers per plant and Number of fruits per plant

OF	IF									
	Number of flowers per plant					Number of fruits per plant				
	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)
CM + BRS	179.53	152.47	157.11	149.50	159.65	208.45	200.86	204.75	201.14	203.80
CM + MC	141.82	114.77	119.40	111.80	121.94	176.41	168.82	172.71	169.10	171.76
CM + GC	171.07	144.02	148.65	141.05	151.19	186.62	179.03	182.92	179.31	181.97
CM + HA	165.86	138.81	143.44	135.84	145.99	198.66	191.07	194.96	191.35	194.01
CM + SW	141.65	114.60	119.23	111.63	121.78	183.78	176.20	180.09	176.48	179.13
CM	140.70	113.64	118.28	110.67	120.82*	171.16	163.57	167.46	163.85	166.51*
Mean (IF)	156.77	129.72	134.35	126.75*		187.51	179.92*	183.81	180.20	
	(OF) = 0.81; (IF) = 1.50 ; (OF X IF) = 2.68				(OF) = 1.12 (IF) = 1.45; (OF X IF) =2.95					

SST= starter solution technology; BSN=NPK based on nutrition; CM=chicken manur e; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed.The numbers in the columns and the rows followed by the * are significantly different according to the LSD (P< 0.05).

Table 7: Effect of OF, IF, and their interaction (OF x IF) treatments on Fruit length (cm) and fruit diameter (mm)

OF	IF									
	Fruit length (cm)					Fruit diameter (mm)				
	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)
CM + BRS	16.89	16.85	16.92	16.88	16.89	0.86	0.86	0.87	0.86	0.86
CM + MC	16.89	16.85	16.92	16.87	16.88	0.85	0.85	0.86	0.85	0.85
CM + GC	16.82	16.78	16.85	16.80	16.81	0.86	0.86	0.87	0.86	0.86
CM + HA	16.90	16.86	16.93	16.87	16.90	0.87	0.86	0.88	0.86	0.87
CM + SW	16.86	16.82	16.89	16.85	16.86	0.86	0.86	0.87	0.86	0.86
CM	16.82	16.78	16.85	16.80	16.81	0.85	0.84	0.86	0.84	0.85
Mean (IF)	16.86	16.82	16.89	16.85		0.86	0.85	0.87	0.85	
	(OF) = 1.18; (IF) = 1.22 ; (OF X IF) = 2.84				(OF) = 1.26 (IF) = 1.41; (OF X IF) =2.94					

SST= starter solution technology; BSN=NPK based on nutrition; CM=chicken manur e; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed

in chili plants, as noted by Malik *et al*. (2020) and Sahu *et al*. (2019).

Yield performance

The combination of CM with BRS resulted in an average fruit weight of 7.45 g and yields of 13.07 t/ha (Table 8). Comparable results were obtained with CM + MC and CM + GC, averaging 7.34 g in weight and 12.27–12.47 t/ha in yield. In contrast, SST + NPK at 1,000 kg/ha recorded a lower yield, emphasizing the superior effect of organic amendments. Integrating NPK fertilizers with organic amendments substantially boosts chili yield by ensuring optimal nutrient availability during the entire growth process of the plant (Anatalia *et al*., 2022; Djoufack *et al*., 2025; Arthanawa *et al*., 2022). Applying foliar fertilizers during the vegetative phase ensures nutrient sufficiency in the generative phase, improving fruit production. Studies indicate that NPK application every 15 days, combined with foliar treatments, stimulates branch formation, cumulative fruit count, and fruit weight, leading to higher overall yield (Ghanbari and Nejad, 2021). The implementation of IPNM significantly improved the nutrient use efficiency (NUE) of N, P, and K compared to conventional fertilizer practices. The combination of OF inputs (such as CM and BRS) with IF (NPK and SST) in IPNM treatments led to an enhancement in nutrient availability within the root zone, attributed to improved soil structure, heightened microbial activity,

Table 8: Effect of OF, IF, and their interaction (OF x IF) treatments on average fruit weight (g) and fruit yield per hectare (t/ha)

OF	IF									
	Average Fruit weight (g)					Fruit yield (t ha^{1})				
	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)	SST + NPK 1000 kg/ha	SST + NPK 500 kg/ha	SST + NPK BSN	NPK 1000 kg/ha	Mean (OF)
CM + BRS	7.43	7.45	7.46	7.47	7.45	13.65	13.02	13.27	12.35	13.07
CM + MC	7.35	7.34	7.35	7.32	7.34	12.84	12.21	12.46	11.54	12.27
CM + GC	7.344	7.33	7.34	7.31	7.33	13.05	12.42	12.66	11.75	12.47
CM + HA	7.43	7.42	7.43	7.41	7.42	13.09	12.47	12.71	11.79	12.52
CM + SW	7.44	7.42	7.43	7.41	7.42	12.69	12.07	12.31	11.39	12.12
CM	7.17	7.15	7.16	7.13	7.16	12.42	11.79	12.04	11.12	11.84*
Mean (IF)	7.37	7.35	7.36	7.33		12.95	12.33	12.57	11.66*	
	(OF) = 1.25; (IF) = 1.21 ; (OF X IF) = 2.64					(OF) = 1.21 (IF) = 1.14; (OF X IF) =2.95				

SST= starter solution technology; BSN=NPK based on nutrition; CM=chicken manur e; BRS=bamboo rhizosphere soil; MC= mycorhyza compost; GC=glio compost; HA=humic acid; SW=seaweed.The numbers in the columns and the rows followed by the * are significantly different according to the LSD (P< 0.05).

and better moisture retention. This facilitated more effective nutrient uptake, particularly in early growth stages, and reduced nutrient losses through leaching and volatilization problems commonly associated with sole reliance on synthetic fertilizers. The slow release of nutrients from organic amendments worked in tandem with the quick availability from inorganic sources, ensuring a continuous nutrient supply during the entire crop cycle. The study revealed significant synergistic effects between OF and IF under the IPNM system, which contributed substantially to improved chili plant performance. Combinations such as CM, BRS, and NPK fertilizers, especially when applied with SST, demonstrated enhanced nutrient use efficiency, better root development, and increased microbial activity in the soil. These interactions led to improved plant growth, greater resistance to pests and diseases, and an increase in yield up to 13.27 t/ha. The results highlight the necessity of meticulously balancing and timing both organic and inorganic inputs to enhance their complementary roles in fostering sustainable and productive chili cultivation.

Muradi *et al*. (2023) revealed that the growth of fruit length is propelled by an increase in leaf production, leading to enhanced photosynthetic efficiency and carbohydrate generation. The effective translocation of assimilates from source tissues (leaves) to sink organs (reproductive parts) contributes to fruit length expansion, supporting optimal fruit development (Rowland *et al*., 2019). Reports indicate that the integration of starter solutions with cow manure and standard IF has led to improved chili growth and higher marketable yield in acidic soils with low fertility. OF and IF starter solutions both showed benefits, particularly in the early growth stages, although they did not always translate into significantly higher total marketable yield (Susila *et al*., 2016). The application of IPNM in acidic soils as a bioresource to show how CM with BRS and IF (SST + NPK) improves chili pepper growth, physiological parameters, pest and disease resistance, and yield performance. In contrast previous to studies that mainly dealt with organic or inorganic amendments, this study underscores a synergistic tri-component approach that boosts plant vigor, enhances photosynthetic efficiency, and fosters soil microbial activity, while simultaneously reducing the prevalence of insects and diseases. Furthermore, the unique application of BRS as a natural inoculant and pest-suppressive agent presents an environmentally benign alternative that promotes plant defense activation and long-term nutrient cycling, providing a comprehensive paradigm for IPNM in chili agriculture. The integration of SST with NPK and OF inputs, specifically CM and BRS, outperformed the NPK-only treatment across multiple growth, yield, and health-related parameters in chili pepper cultivation. Plants that underwent the IPNM method showed enhanced vegetative growth, which included greater plant height, a higher number of leaves, and an expanded canopy diameter. In addition, fruit yield increased markedly, with higher fruit number per plant and greater average fruit weight compared to the control. Moreover, the integrated treatment enhanced pest and disease resistance, as evidenced

by reduced incidence of common foliar pathogens and pest damage. The enhanced performance can be credited to the combined effect of organic and inorganic inputs, which probably increased nutrient availability, encouraged beneficial microbial activity in the rhizosphere, and improved the physical and chemical properties of the soil. This holistic improvement suggests that IPNM not only boosts productivity but also contributes to more resilient and sustainable chili pepper production systems under tropical conditions. While this study provides valuable insights into the effectiveness of IPNM using a combination of OF and IF inputs, several limitations must be acknowledged. First, the experiment was conducted over a single cropping season and at a specific field site with acidic soil conditions. This constrained temporal and spatial framework may not adequately reflect seasonal variations, prolonged soil dynamics, or the broader relevance of the findings across different agroecological regions. Second, although the study demonstrated improved plant growth, yield, and resistance to pests and diseases, the underlying biological mechanisms, particularly the roles of soil microbiota and nutrient uptake pathways, were not directly assessed. Furthermore, while OF inputs such as CM and BRS likely influenced microbial community dynamics, no metagenomic or microbial profiling was performed to confirm these interactions. Furthermore, the study concentrated mainly on agronomic results (growth, biomass, and yield), without evaluating economic viability, nutrient use efficiency, or potential environmental effects such as nutrient leaching or greenhouse gas emissions. Future research should address these limitations through long-term, multi-season field trials conducted in diverse agroecosystems to assess the stability and reproducibility of IPNM effects. The long-term application of IPNM practices is expected to restore and maintain soil fertility, support microbial health, and sustain high yields with reduced environmental impact. The combined advantages of IPNM establish it as a scalable and sustainable nutrient management strategy, which is especially beneficial in areas facing soil degradation or resource limitations. Incorporating soil microbiome analyses using molecular techniques (e.g., 16S rRNA sequencing or metagenomics) would help elucidate how OF and IF inputs modulate microbial communities and contribute to plant health. Studies focused on mechanisms related to nutrient uptake efficiency, root design, and plant responses to stress would yield greater insights into the physiological benefits associated with integrated nutrient management. Furthermore, integrating life cycle assessments and economic analyses would allow for evaluation of the sustainability and feasibility of IPNM practices for smallholder farmers. Lastly, given the observed reduction in disease incidence, future work should explore the potential for IPNM to be integrated with pest and disease management strategies, possibly in combination with biological control agents or predictive disease models. Continuous observation over the seasons is suggested to evaluate advantages and facilitate the refinement of input combinations. Addressing these research gaps will enhance the scientific robustness and practical relevance of IPNM as a sustainable approach to crop production.

CONCLUSION

The findings of this study show that IPNM, which combines OF and IF, significantly improves chili pepper (*Capsicum annuum* var. annuum) growth, biomass production, resistance to pests and diseases, and overall yield. The combined use of CM, BRS, and SST + NPK fertilizers resulted in improvements in plant vigor, with yields reaching up to 13.27 t/ha and biomass increases of 15–20% compared to using IF alone. This evidence underscores the capacity of IPNM to improve nutrient absorption, boost physiological performance, and fortify the plant's inherent defenses against biotic stressors. Beyond immediate agronomic benefits, IPNM contributes to long-term soil health and environmental sustainability. Incorporating organic inputs such as CM and BRS strengthens soil structure, promotes microbial activity, and increases the availability of nutrients. These changes not only reduce dependency on synthetic inputs but also help mitigate their associated environmental impacts, including soil degradation and nutrient leaching. By encouraging the use of locally available organic materials, IPNM fosters circular nutrient economies and supports more resilient agricultural ecosystems, especially in challenging environments such as acidic soils. Moreover, the observed improvements in soil fertility and plant performance suggest that IPNM is a viable strategy for sustainable intensification, an approach increasingly necessary in the face of growing global food demand and shrinking arable

land. By merging ecological concepts with standard agricultural practices, IPNM presents a harmonious, environmentally sustainable, and scalable framework for crop production. Additionally, the increased microbial activity and diversity in organically enriched soils improve nutrient mineralization and enhance the rhizosphere environment, creating unfavorable conditions for pathogen establishment. The capacity for biological buffering lessens the necessity for chemical pesticides, promoting a safer and more sustainable farming system. By reducing pest and disease pressure naturally, IPNM not only minimizes crop losses but also lowers production costs and mitigates ecological risks associated with pesticide overuse. Nonetheless, while the short-term benefits of IPNM are apparent, it is vital to conduct further long-term studies to understand its cumulative effects on soil microbial diversity, nutrient cycling, carbon sequestration, and the resilience of agroecosystems across diverse climatic conditions and farming practices. Such research will help refine the strategy for broader implementation and contribute to the development of sustainable agriculture systems that are productive, adaptable, and ecologically sound.

AUTHOR CONTRIBUTIONS

R. Rosliani has contributed to conceptualization, methodology, validation, investigation, and writing the original draft. W. Setiawati contributed as the corresponding author, methodology, validation, investigation, and writing the original draft. M. Prathama contributed to methodology, validation, investigation, data analysis, and interpretation of the results. R. Murtiningsih contributed to the investigation, provided resources, wrote the original draft, and edited. T.K. Moekasan contributed to conceptualization, methodology, validation, investigation, and writing the original draft. N. Gunaeni contributed to conceptualization, methodology, validation, investigation, and writing the original draft. N. Gunadi contributed to methodology, validation, investigation, and data analysis. Eli Korlina contributed to the investigation, provided resources, wrote the original draft, B.K. Udiarto contributed to the supervision, conceptualization, methodology, validation, investigation, and writing of the original draft. Y. Suryadi prepared the validation, writing, and edited the manuscript. All co-authors reviewed and approved the final version of the manuscript before submission.

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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.

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ABBREVIATIONS

%	Percent
°C	Degree Celcius
ANOVA	Analysis of variance
BRS	Bamboo rhizosphere soil
C	Carbon
cm	Centimeter
CM	Chicken manure
cv	Cultivar
C/N	Carbon-Nitrogen ratio
Ca	Calcium
cmol	Centimole
DAP	Days after planting
g	Grams
GC	Glio-compost
HA	Humic acid
ha	Hectares
HSD	Honestly significant difference
IF	Inorganic fertilizer
IPNM	Integrated plant nutrient management
IVegRI	Indonesian Vegetable Research Institute
K	Potasium
kg	Kilogram
L	Liter
LSD	Least significant difference
m	Meter
m^2	Square meter
MC	Mycorhiza-compost
Mg	Magnesium
min	Minutes
mL/L	Milliliter per liter
mm	Millimeter
m^2	Square meter
N	Nitogen
NaCl	Sodium chloride
NPK	Nitrogen-Phosphorus-Kalium
NUE	Nutrient use efficiency
OF	Organic fertilizer
P	probability
pH-H_2O	Potential hydrogen-water
pH-KCl	Potential hydrogen-Potassium chloride
P_2O_5	Diphosphorus pentoxide
s	Seconds
S	Sulfur
SAS	Statistical analysis software
SST	Starter solution technology
SW	Seaweed extract
t/ha	Tons per hectare

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CASE STUDY

Environmental impacts of pile driving-induced ground vibrations on human comfort and structural integrity

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ABSTRACT

BACKGROUND AND OBJECTIVES: Pile driving is widely used in infrastructure projects but it often generates strong ground vibrations that can spread into surrounding neighborhoods. These vibrations are more than just an engineering issue; they can be understood as a type of environmental pollution, similar to noise. Communities near construction sites frequently experience reduced comfort, annoyance, and even health concerns, while fragile houses and public facilities may be at risk of structural damage. In tropical alluvial soils, such as those found in Yogyakarta, Indonesia, low-frequency waves travel efficiently over long distances, which magnifies their environmental consequences. The main objectives of this study were to evaluate pile-driving vibrations as an environmental hazard, linking the technical results to wider concerns about human well-being and sustainable urban development.

METHODS: Measurements were conducted during railway construction near Yogyakarta International Airport in Kulon Progo Regency. A triaxial geophone recorded vibrations at three distances: 10, 50, and 70 meters. Parameters included peak particle velocity, ground displacement, and dominant frequency. A power-law regression was utilized to model the decrease of vibration energy with increasing distance. Results were assessed against Indonesian regulations and compared with international vibration standards commonly applied in environmental monitoring in Germany and the United Kingdom.

FINDINGS: The analysis showed that low-frequency waves between 5 and 15 hertz were dominant. These intersected with the natural frequencies of nearby residential properties, which raised concerns regarding environmental impact and safety. At 10 meters from the pile, peak particle velocity reached 5.6 millimeters per second, far above both the comfort limit of 0.3 millimeters per second and the damage threshold of 2.0 millimeters per second. At distances of 50 meters and 70 meters, the values of peak particle velocity dropped, but they still stayed above the comfort thresholds. A buffer of around 60 meters was needed to avoid discomfort, while 30 meters was necessary to prevent building damage.

CONCLUSION: The results demonstrate that pile-driving vibrations should be managed as a form of environmental pollution. They diminish community stability, pose risks to vulnerable infrastructures, and complicate sustainable advancement in tropical locales. The findings advocate for the inclusion of vibration monitoring in evaluating environmental impacts, alongside the development of regulations and buffer zones to ensure the protection of residents and infrastructure.

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INTRODUCTION

The rapid pace of infrastructure development in densely populated areas has intensified the importance of evaluating construction-induced ground vibrations. Among the different sources of vibrations associated with construction, diesel-hammer pile driving is especially important as it creates powerful ground motions that can travel into nearby residential neighborhoods (Colaço *et al.,* 2022). Such vibrations generally result in two main consequences: discomfort to humans and potential structural damage to buildings (Guo *et al.,* 2023; Andriyani *et al.,* 2024). A recent numerical investigation by Abdelsalam and Seyedi (2025) emphasized that vibration responses are strongly governed by the interaction between the energy source and local soil properties (Hawrami and Baset, 2024). In response to these issue, multiple national and international standards have been set up to control allowable vibration levels. In Indonesia, the Ministry of Environment Decree No. 49/1996 as regulated by the Indonesian vibration limits MERI, (1996) specifies threshold values for both human comfort and structural safety. Internationally, DIN 4150-3 (1999) (Germany) and BS 7385-2 (1993) (UK) are widely used benchmarks for evaluating damage risk in civil engineering applications (Kuo *et al.,* 2020; Gholami *et al.,* 2023). Regardless of the existence of these regulations, empirical data on pile-driving vibrations in tropical alluvial areas remains insufficient. Unconsolidated sediments characterized by high groundwater levels can amplify low-frequency waves, which often coinciding with the natural frequencies of single-storey masonry structures, thus increasing the risk of resonance (Sofiste *et al.,* 2021). In previous studies conducted in Indonesia, the emphasis has largely been on peak particle velocity (PPV) (Sun *et al.,* 2023; Colaço *et al.,* 2023), without incorporating displacement, dominant frequency, or multi-standard cross-validation. A representative case is the construction of the Yogyakarta International Airport (YIA) railway line in Kalidengen Village, Temon District, Kulon Progo Regency (Fig. 2). The project is positioned near heavily populated residential zones, primarily featuring unreinforced masonry houses. This study advances previous works by integrating multiple field-measured parameters PPV, displacement, and dominant frequency with attenuation modelling in tropical alluvial soils. Through a systematic comparison of outcomes with both Indonesian and international vibration standards, it offers the initial regulation-focused evaluation of the impacts of pile driving in Kalidengen Village. Ground vibrations are increasingly recognized as a form of environmental pollution, similar to noise and air pollution, because they directly affect community well-being, environmental quality, and public health. This study emphasizes the significance of considering vibration as an environmental hazard, particularly in the context of environmental impact assessments (EIA), sustainable construction planning, and safeguarding community well-being. The specific objectives are: 1) To measure PPV, displacement, and dominant frequency. To analyze attenuation trends across frequency ranges. 2) To compare empirical findings with national and international standards. 3) To propose an empirical attenuation model that supports safe construction practices. Additionally, the study points out that vibrations should be regarded as both an environmental and social concern, alongside the technical objectives (Colaço *et al.,* 2021). According to ISO 1997, prolonged exposure to low-frequency vibrations is associated with annoyance, sleep disturbance, and psychosocial stress (ISO, 1997; WHO, 2018). While this study did not include direct surveys of local communities, future investigations in Indonesia should integrate vibration monitoring with community-based assessments (Chen et al., 2024 ; Herdiansyah, 2023; Utami *et al.,* 2025). Utilizing this strategy would provide a more transparent connection between the measured parameters (PPV, displacement, and frequency) and the residents' views on annoyance, health consequences, and their overall well-being (Wang *et al.,* 2024). Establishing this link between technical data and lived experience would provide policymakers with stronger evidence for revising national vibration standards and strengthening environmental impact assessments. Given that systematic studies connecting vibration measurements with community responses remain scarce in Indonesia, this reinforces both the novelty and the urgency of continued research in this field. Beyond the technical domain, vibrations generated by construction activities also produce concrete social and environmental consequences. Monitoring conducted around the Yogyakarta International Airport railway project, for instance, documented rising levels of noise and ground shaking,



Fig. 1: Field vibration measurements during pile driving at the YIA railway project in Kalidengen. (a) Measurement at 10 m from the source (Location 1), (b) measurement at 50 m using the SARA RTS system (Location 2), and (c) measurement at 70 m from the source (Location 3).

accompanied in some cases by tension within nearby communities such as Kalidengen. These observations indicate that local residents do not perceive vibration merely as a minor inconvenience but rather as a genuine threat to everyday comfort and collective well-being. While no formal community surveys were conducted, observational notes and informal discussions with residents revealed widespread concerns about comfort, psychosocial stress, and potential health effects. These qualitative insights complement the objective vibration measurements and highlight the broader human dimension of the impacts. Community responses are often influenced by socio-economic and cultural conditions, since lightweight masonry dwellings and temporary housing structures are more susceptible to cracks and cosmetic deterioration than reinforced buildings. This highlights the necessity of embedding local realities into vibration risk assessments. From a regulatory standpoint, Indonesia continues to rely on Ministerial Decree No. 49/1996 (MERI No. 49/1996), which prescribes threshold values but does not fully reflect the distinctive behavior of tropical alluvial soils. With their high moisture content and unconsolidated layering, these soils tend to magnify low-frequency waves that propagate over long distances. Comparative analysis with international benchmarks such as DIN 4150-3 (Germany) and BS 7385-2 (UK) reveals considerable disparities, suggesting that revisions to national standards are warranted to ensure both contextual relevance and alignment with broader global practices (Chen *et al.,* 2024; Yimsiri *et al.,* 2025). Although vibration evaluation is formally incorporated into Indonesia's Environmental Impact Assessment (AMDAL) for large-scale infrastructure projects, its implementation in practice often prioritizes noise and air pollution, while the issue of vibration receives less systematic attention (Kurniawan *et al.,* 2020; Romianingsih *et al.,* 2023). Recent research argues that the EIA framework should evolve from a procedural requirement into a substantive instrument capable of safeguarding environmental quality and public safety (Caro-González *et al.,* 2023; Park *et al.,* 2025). In densely inhabited areas, however, enforcing wide buffer zones presents difficult trade-offs, as it may reduce land-use efficiency and escalate construction costs. These challenges reinforce the importance of balanced, context-sensitive regulatory updates that integrate both technical and socio-economic considerations (Tan *et al.,* 2022; Dong *et al.,* 2025). The specific objectives are: i) To measure PPV, displacement, and dominant frequency, and to analyze attenuation trends across frequency ranges. ii) To compare empirical findings with national and international standards. iii) To propose an empirical attenuation model that supports safe construction practices. This study was conducted in Kulon Progo District, Indonesia in 2025.

MATERIALS AND METHODS

The field investigation was conducted in Kalidengen Village, Temon District, Kulon Progo Regency, Yogyakarta, an area directly affected by the YIA railway construction project. This densely populated settlement, consisting mainly of single-storey masonry houses, schools, and small commercial buildings, has undergone rapid land-use transformation due to

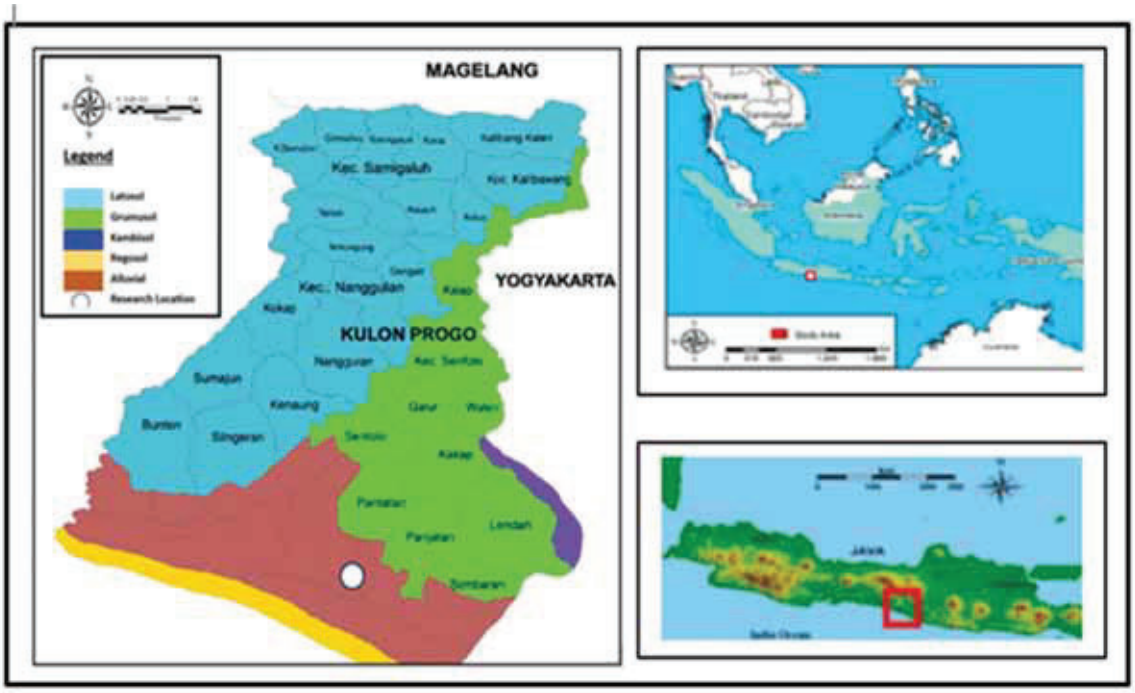

Fig. 2: Geographical distribution of soil types and study location in Kulon Progo District, Indonesia. The map on the left shows soil classifications across Kulon Progo (Latosol, Grumosol, Regosol, Alluvial, and associated landforms), with the research site marked. The upper-right inset indicates the regional context of the study area within Indonesia, while the lower-right inset highlights the location on Java Island

airport development and related infrastructure (Utami *et al.,* 2025). During the months of May and June 2025, ground vibration monitoring was performed at three designated observation points situated roughly 10 meters (m), 50 m, and 70 m from the pile-driving site (Fig. 2). This monitoring coincided with the active installation process installation using a DELMAG D19-42 diesel hammer. The geographic coordinates of the pile-driving source and measurement locations are presented below. Considering the widespread presence of unreinforced masonry houses equipped with lightweight roofs, these structures are viewed as extremely vulnerable to low-frequency vibrations that may cause plaster cracking or surface damage (Herdiansyah, 2023). The coordinates of the source and measurement locations were:

- Pile-driving location: 7°53’49.74” S, 110°04’58.14” E
- Location 1 (~10 m): 7°53’49.52” S, 110°04’57.89” E (Fig. 1a)
- Location 2 (~50 m): 7°53’48.66” S, 110°04’56.87” E (Fig. 1b)
- Location 3 (~70 m): 7°53’48.26” S, 110°04’56.40” E (Fig. 1c)

Vibration monitoring

Ground vibrations were measured using a SARA RTS vibration monitor (SARA Instruments, Perugia, Italy) equipped with triaxial sensors capable of recording real-time particle velocity and displacement (Fig. 2). Similar monitoring systems have been applied in previous environmental vibration studies (Kazemzadeh *et al.,* 2023; Srivanit *et al.,* 2024).

Pile-driving operations

Pile installation was executed utilizing the Delmag D19-42 diesel hammer, a method frequently employed for deep foundations in deep foundations within dense or hard soils and is also known for generating significant vibrations. The hammer operates with a free-fall ram of approximately 1,900 kilograms (kg) and a stroke length of ~4,200 millimeters (mm), delivering up to ~78 kilonewton meters (kNm) of impact energy at 40–60 blows per

Table 1 : Mechanical specifications of the Delmag D19-42 diesel hammer

Parameter	Specification
Ram weight	~1,900 kg
Stroke length	~4,200 mm
Maximum impact energy	~78 kNm
Impact frequency	40–60 blows/min
Total hammer weight	~3,400 kg
Guide type	Vertical leader

Table 2: Technical specifications of the vibration monitoring equipment

Parameter	Specification
Instrument type	SARA RTS ground vibration monitoring
Sensor	Triaxial geophone (X, Y, Z)
Particle velocity range	0.01–250 mm/s
Velocity resolution	0.01 mm/s
Frequency range	1–250 Hz
Measured parameters	Particle velocity (mm/s), displacement (μm), frequency (Hz)
Accuracy	±5 percent (%) of reading
Power supply	Internal battery + optional external power
Data storage	Internal memory, exportable to PC
Referenced standards	DIN 4150-3:1999, ISO 4866, MERI No. 49/1996

minute (min). These operational attributes result in the creation of both low and mid frequencies ground motions, rendering them appropriate for conducting attenuation studies in alluvial soils (Sun *et al.,* 2023). Specifications are provided in Table 1.

This study focused on a single hammer type (Delmag D19-42), which is one of the most commonly used diesel hammers in Indonesian infrastructure projects. Although variability in vibration amplitudes across different hammer energies or pile dimensions was not assessed, this hammer type provides a representative case for high-energy pile driving in dense soils. Future studies may extend the analysis to alternative hammer types and pile geometries.

Ground vibration monitoring system

The SARA RTS system employed high-resolution triaxial geophones with resolution 0.01 millimeter per second (mm/s); frequency range 1–250 hertz (Hz) , installed directly on the ground surface in compliance with DIN 45669-1 (2005). Sensors were connected to a digital logger, and data were processed using fast fourier transform (FFT) to identify dominant frequency components. Technical specifications are listed in Table 2.

Measured parameters

Field investigations were conducted at three observation points located 10, 50, and 70 m from the pile-driving source. The choice of these distances reflected a combination of practical site constraints, including accessibility, safety requirements, and agreements with the contractor (Utepov *et al.,* 2025). The nearest point (10 m) represented the critical zone where vibration levels were expected to be most intense, while the two farther points captured the transition and attenuation phases. Although the spacing between points was relatively limited, the dataset was sufficient to demonstrate attenuation trends in soft alluvial soils (Utepov *et al.,* 2025). Future research may extend these observations by incorporating intermediate distances to refine the attenuation profile (Utepov *et al.,* 2025). In addition to distance effects, local geotechnical and environmental conditions were also considered. The site is underlain by thick alluvial deposits with a high groundwater table, a combination that influences the propagation of vibration waves. Furthermore, seasonal variations between wet and dry periods are expected to modify soil damping capacity (Avci *et al.,* 2022). While the present study was carried out during a single measurement campaign, these

environmental variables should be integrated into longer-term monitoring efforts to provide a more complete picture. Vibration data were recorded along three axes (X, Y, and Z), thereby capturing vertical, horizontal, and torsional components. For analytical clarity, however, only the dominant components were emphasized in the discussion. This simplification ensured interpretive focus while still adequately reflecting the overall vibration response of the soil-structure system (Abdelsalam and Seyedi, 2025).

Measured parameters

The analysis focused on three primary parameters:

1. PPV, mm/s: Standard indicator of structural damage risk, evaluated against MERI No. 49/1996, DIN 4150-3:1999, and BS 7385-2:1993 (Massarsch and Fellenius, 2014).

2. Peak displacement as micrometer (µm): Represents maximum soil particle movement, critical for brittle materials such as plaster, ceramics, and glass (Guo *et al.,* 2023).

3. Dominant frequency (Hz): Determines resonance risk, especially when vibration frequency aligns with the natural frequency of single-storey masonry buildings (Guo *et al.,* 2023).

These parameters are related by the harmonic motion, using Eq. 1 (Guo *et al.,* 2023):

$$v = 2\pi f x v = 2\pi f x \quad (1)$$

Where, v is PPV (mm/s), f is frequency (Hz), and x is peak displacement (mm). The focus of the measurements was on the 4–63 Hz frequency band, as it is most pertinent to human perception and the structural behavior of unreinforced masonry houses.

Soil characteristics of the study area

Kulon Progo Regency contains five dominant soil groups: Latosol (45.08%), Grumusol (28.63%), alluvial (20.23%), Regosol (4.90%), and Cambisol (1.15%) (Litasari *et al.,* 2022). The Kalidengen study site lies in the alluvial zone (Fig. 2), characterized by loose, fine- to medium-grained sediments with low stiffness and weak damping properties. These conditions promote long-distance propagation of Rayleigh and Love waves, especially within the 8–25 Hz range (Asnawi *et al.,* 2022). Previous studies indicate that PPV and displacement can remain elevated up to ~70 m from the source, confirming the amplification effect of alluvial deposits. Such conditions highlight the importance of soil-specific mitigation strategies to protect both human comfort and structural integrity (Lin *et al.,* 2024).

RESULTS AND DISCUSSION

To evaluate the potential effects of pile-driving vibrations on human comfort and structural safety, the measured PPV and peak displacement values were compared against three regulatory standards; the Indonesian MERI No. 49/1996 (Indonesia), DIN 4150-3 (Germany), and BS 7385-2 (United Kingdom). The measured peak particle velocity (PPV, mm/s) at three observation points (10 m, 50 m, and 70 m) in Kalidengen Village is presented in Table 3. Combining displacement data and PPV yields a more complete evaluation, especially in the low-frequency domain (4–10 Hz), where particle displacements are comparatively substantial. This frequency range is critical since excessive displacements can amplify structural responses and increase the likelihood of damage to brittle components such as plaster and masonry (Kazemzadeh *et al.* , 2023).

As outlined in Table 3, the PPV values showed an exponential decline with rising frequency at every observation points, aligning with theoretical models of vibration attenuation in alluvial soils influenced by geometric spreading and material damping (Ni *et al.* , 2017).

- Location 1 (10 m): At a frequency of 4 Hz, the PPV reached a maximum of 20.69 mm/s, which exceeded all thresholds. indicating a likelihood of causing human discomfort as well as cosmetic to minor structural damage.
- Location 2 (50 m): Maximum PPV of 9.98 mm/s at 4 Hz exceeded MERI No. 49/1996 and DIN 4150-3 limits up to 6.3 Hz but remained below BS thresholds, indicating moderate risk, primarily discomfort and cosmetic effects.
- Location 3 (70 m): Maximum PPV of 8.14 mm/s at 4 Hz exceeded only the Indonesian threshold, with values otherwise within DIN 4150-3, and BS 7385-2 limits, suggesting more effective attenuation due to higher damping of the alluvial deposits.

Residual fitting analysis of exponential PPV decay

Analysis of the residuals from the exponential fitting revealed a satisfactory match, with deviations usually falling within ±5–7%, which is consistent with

Table 3: Measured PPV, (mm/s) at three observation points (10 m, 50 m, and 70 m) across selected frequency ranges, compared with threshold values specified in Indonesian regulation (MERI No. 49/1996), German standard (DIN 4150-3), and British standard (BS 7385-2)

Frekuensi (Hz)	Location			Regulation		
	1 (10 m)	2 (50 m)	3 (70 m)	MERI No. 49/1996	DIN 4150-3	BS 7385-2
	20.69	9.98	8.14	2.79	5	4
4	17.32	9.01	6.72	2.79	5	4
5	9.35	6.85	5.69	2.79	5	4
6.3	8.78	4.33	4.32	2.79	5	4
8	6.49	3.59	3.17	2.79	5	4
10	4.63	3.16	1.62	2.79	5.625	4
12.5	4.33	1.86	0.75	2.79	6.5	12
16	2.2	0.87	0.35	2.79	7.5	12
20	1.38	0.42	0.12	2.79	8.75	12
25	0.58	0.24	0.04	2.79	10.375	12
31.5	0.25	0.12	0.03	2.79	12.5	12
40	0.18	0.08	0.02	2.79	15	50
50	0.11	0.038	0.004	2.79	15	50

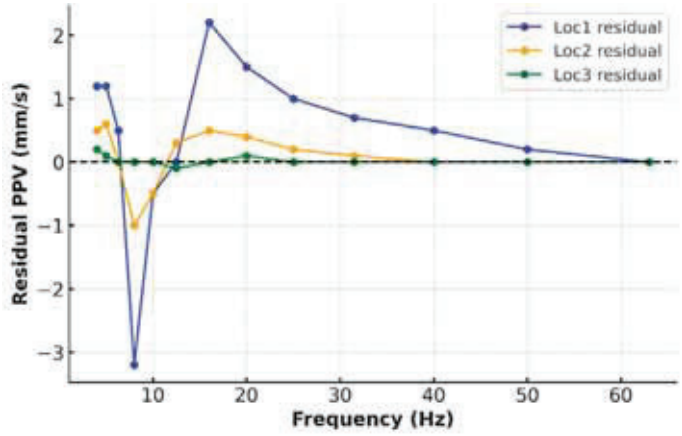

Fig. 3: Residuals are plotted for locations at 10 m, 50 m, and 70 m from the pile-driving source. X-axis = Frequency (Hz); Y-axis = Residual PPV (mm/s).Dashed line indicates the zero-residual baseline, highlighting minor anomalies around 4–6.3 Hz and 16 Hz

previous investigations into vibration attenuation in alluvial soils (Ni *et al.,* 2017). Minor irregularities were detected at frequencies of 4–6.3 Hz and approximately 16 Hz, potentially indicating partial resonance effects and variations in soil composition (Auersch and Said, 2010). These results confirm that the empirical attenuation models are sufficiently robust for practical applications (Abouelmaty *et al.,* 2025; Massarsch and Fellenius, 2014; Orozco-Herrera *et al.,* 2022). Supplementary material includes extra figures and detailed residual plots to prevent excessive technical distractions from the overall environmental context of the study. The main residual fitting results are presented in Fig. 3, which highlights the deviations across frequency ranges and supports the robustness of the exponential model.

The risk zoning (Fig. 4) demonstrated:

- Location 1 as high-risk (4–5 Hz).
- Location 2 as moderate-risk (4–12.5 Hz).
- Location 3 as predominantly safe, with minor exceedances at 4 Hz.

These patterns reflect the sandy-clay alluvial deposits with high moisture content in Kalidengen, which amplify low-frequency vibrations (1–10 Hz). The findings underscore the necessity of merging frequency-domain analysis with regulatory guidelines to enhance mitigation strategies.

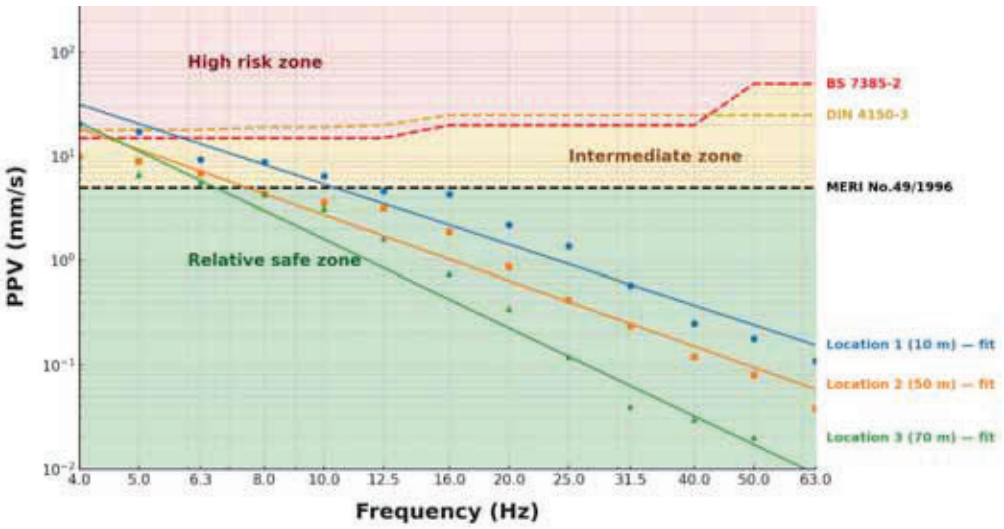

Fig. 4: Comparison of PPV vs Frequency limits from MERI No.49/1996 (flat 5 mm/s), DIN 4150-3 (dashed golden), and BS 7385-2 (stepped dashed red), plus log–log power-law fits to field data at 10 m, 50 m, and 70 m. Color zones: green = relative safe (< MERI), yellow = intermediate (MERI–BS), red = high risk (≥ BS)

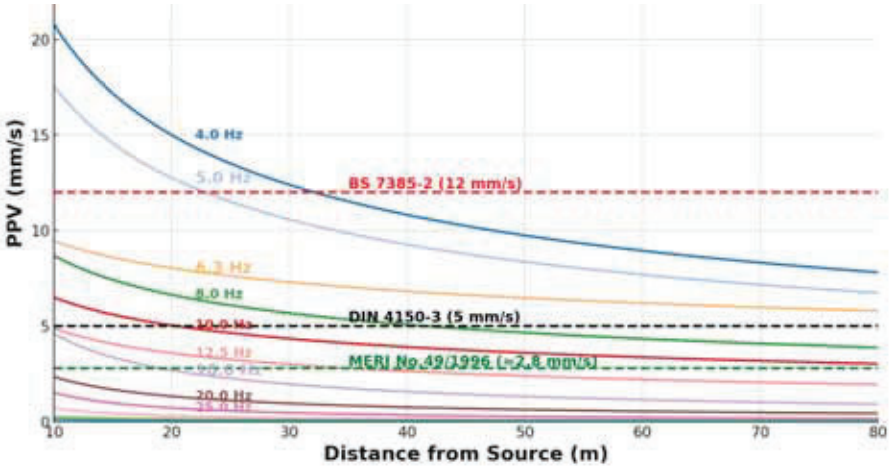

Fig. 5: Attenuation of PPV with distance at various frequencies in Kalidengen Village, regression curves compared against regulatory limits from MERI No.49/1996 (≈2.8 mm/s), DIN 4150-3 (5 mm/s), and BS 7385-2 (12 mm/s)

PPV attenuation analysis: safe distance implications

The attenuation of PPV with distance was well represented by a power-law model (Fig. 5). A small attenuation exponent indicated slow dissipation of vibrations in saturated alluvial soils, consistent with findings elsewhere (Sharma *et al.,* 2025 ; Utepov *et al.,* 2025; Wei *et al.*, 2022). Proposed mitigation techniques encompass pre-drilling, vibratory pile driving , and PGP piles , which can collectively reduce vibration impacts by 20–30% (Shao *et al.*, 2023).

Exponential attenuation pattern of PPV and safe distance estimation

The attenuation analysis of pile-driving vibrations in Kalidengen Village reveals that low-frequency components (4–6 Hz) exhibited high initial PPV values that persisted over extended distances (Yimsiri *et al.,* 2025), consistently exceeding national Indonesia MERI, (1996) and international (DIN 4150-3 and BS 7385-2) thresholds. In order to quantify safe buffer zones, regression-based attenuation equations were

Table 4: Empirical equations for peak particle velocity (PPV) attenuation with distance across selected frequency ranges, and corresponding calculated safe distances (m) based on threshold limits from Indonesian regulation (MERI No. 49/1996, 2 mm/s), German standard (DIN 4150-3, 5 mm/s), and British standard (BS 7385-2, 12 mm/s)

Frequency (Hz)	PPV (mm/s)	Safe distance		
		MERI No. 49/1996 (2 mm/s)	DIN 4150-3 (5 mm/s)	BS 7385-2 (12 mm/s)
4	$61.4729 \times d^{-0.4711}$	1.293.6	207.3	31.5
6.3	$16.2505 \times d^{-0.2357}$	8.024.0	135.6	3.1
10	$15.1492 \times d^{-0.3681}$	247.1	17.1	1.8
12.5	$13.5246 \times d^{-0.4442}$	226.9	13.5	1.4
16	$27.8809 \times d^{-0.7823}$	41.4	3.0	0.9
20	$15.7336 \times d^{-0.8284}$	15.2	2.2	0.8
25	$18.5565 \times d^{-1.0922}$	8.3	1.3	0.6
31.5	$8.6133 \times d^{-1.1135}$	5.6	0.9	0.4
40	$2.1489 \times d^{-0.8896}$	1.6	0.5	0.3
50	$1.7027 \times d^{-0.9318}$	0.9	0.4	0.2
63	$3.0825 \times d^{-1.3740}$	1.3	0.8	0.3

employed to determine setback distances for each regulatory framework (Table 4). At 4–6.3 Hz, safe distances varied dramatically depending on the standard.

In contrast, medium frequencies (6.3–10 Hz) attenuated more rapidly and fell below DIN limits at intermediate distances. High frequencies (>20 Hz) remained well below all standards even near the vibration source. This pattern indicates that low-frequency vibrations represent the most significant risk in alluvial soils. They can propagate over long distances with minimal attenuation (Rezaei *et al.,* 2016 ; Sun *et al.,* 2023). The estimates reached several kilometers under the Indonesian threshold, hundreds of meters under DIN 4150-3, and only tens of meters under BS 7385-2. When frequencies rise above 20 Hz, the safe distances tend to converge to small values. They were typically <10 m for Indonesian regulations and <1 m for BS 7385-2. These findings suggest that high-frequency components present negligible risks. Two significant implications can be inferred. First, regulatory discrepancies are most pronounced in the low-frequency range, which emphasizes the need for standard-specific assessments in alluvial regions (Svinkin., 2013). Second, the ongoing existence of low-frequency waves emphasizes the significance of including frequency-domain analysis in construction standards. Relying only on PPV thresholds may underestimate risks to human comfort and structural integrity. Comparison of safe distance as a function of frequency for the MERI No. 49/1996 (2 mm/s), DIN 4150-3 (5 mm/s), and BS 7385-2 (12 mm/s) is shown in Fig. 6.

Distribution of particle displacement vs frequency

As shown in Table 5, displacements were largest in the 4–6.3 Hz band, exceeding BS 7385-2 thresholds at 10 m and remaining significant up to 70 m. These results underscore the necessity of conducting displacement analysis, as PPV thresholds by themselves might not accurately reflect the risks posed to sensitive structural components like plaster, glass, or ceramics. International standards identified higher risks than Indonesian thresholds, suggesting the need for region-specific revisions.

Residual analysis of displacement attenuation

Residual analysis of displacement attenuation also showed satisfactory model fits, with typical deviations within ±5–7%, in line with earlier experimental and numerical studies on vibration decay in soft soils (Ni *et al.,* 2017). Minor discrepancies at lower frequencies (4–6.3 Hz) and approximately 16 Hz are likely indicative of resonance phenomena and the heterogeneity of the soil (Auersch and Said, 2010). In general, the outcomes support the notion that the attenuation models are reliably suitable for practical implementation, consistent with prior engineering evaluations pile-driving vibrations (Massarsch and Fellenius, 2014). More detailed residual plots are provided in the supplementary material. Fig. 7. illustrates the residuals of exponential fitting for particle displacement, highlighting deviations at low frequencies (4–20 Hz) and stabilization at higher frequencies.

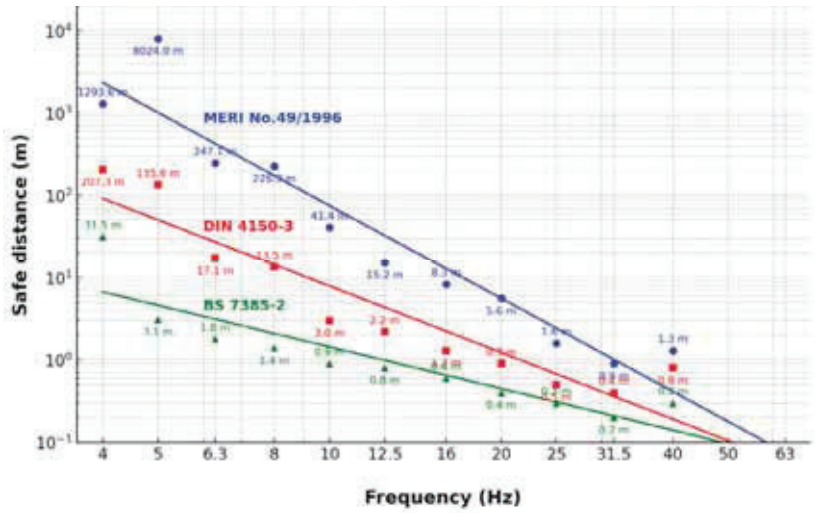

Fig. 6: Safe distances for PPV at various frequencies in Kalidengen Village according to MERI No.49/1996, DIN 4150-3, and BS 7385-2. The log–log plot shows that safe distance decreases as frequency increases, with the strictest requirements given by MERI No.49/1996, followed by DIN 4150-3 and BS 7385-2. Lower-frequency vibrations require larger separation distances to remain within regulatory limits, while higher frequencies permit shorter safe distances

Table 5: Measured particle displacement (μm) at three observation points (10 m, 50 m, and 70 m) across selected frequency ranges, compared with reference displacement limits specified in Indonesian regulation (MERI No. 49/1996), German standard (DIN 4150-3), and British standard (BS 7385-2)

Frequency (Hz)	Location			Regulation		
	1 (10 m)	2 (50 m)	3 (70 m)	MERI No. 49/1996	DIN 4150-3	BS 7385-2
	689.22	397.41	323.95	111.01	198.94	159.15
4	658.72	286.92	181.29	88.81	159.15	127.32
5	236.42	173.26	169.91	70.48	126.31	101.05
6.3	92.15	86.3	85.92	55.51	99.47	79.58
8	103.36	57.21	50.52	44.4	79.58	63.66
10	111.89	40.32	20.69	35.52	71.62	50.93
12.5	43.12	18.53	7.46	27.75	64.66	119.37
16	17.55	6.96	2.83	22.2	59.68	95.49
20	8.78	2.71	0.79	17.76	55.7	76.39
25	2.93	1.23	0.22	14.1	52.42	60.63
31.5	0.72	0.49	0.12	11.1	49.74	47.75
40	0.64	0.25	0.08	8.88	47.75	159.15
50	0.36	0.096	0.011	7.05	37.89	126.31

Vibration risk zoning based on displacement–frequency

Risk zoning (Fig. 8) revealed:

- High-risk: Location 1 at 4–8 Hz, exceeding BS 7385-2 thresholds.
- Moderate-risk: Location 2 between DIN 4150-3 and BS 7385-2 thresholds.
- Low-risk: Displacements between Indonesian and DIN 4150-3 limits.
- Safe: Below Indonesian thresholds.

At a distance of 70 m, displacements surpassed Indonesian limits at 4 Hz, indicating that low-frequency vibrations can propagate over extensive distances and present considerable threats to both comfort and structural stability.

Displacement attenuation and safe distance

Exponential attenuation analysis (Fig. 9 and Table 6) showed that displacements at 4–6.3 Hz yielded extremely long safe distances—up to 885 m under

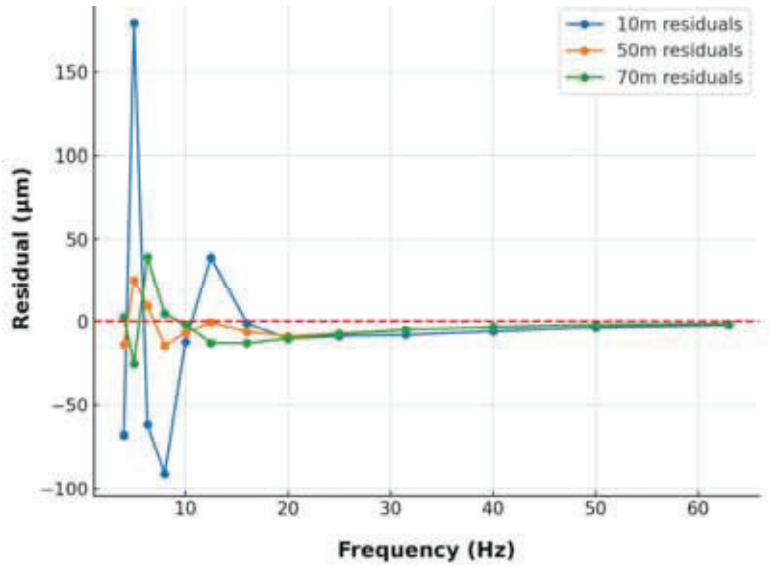

Fig. 7: Residuals of exponential fitting for particle displacement across frequencies at three observation distances (10 m, 50 m, and 70 m). The residuals represent the difference between measured values and fitted exponential models. Large deviations are observed at lower frequencies (4–20 Hz), while residuals tend to stabilize and approach zero at higher frequencies

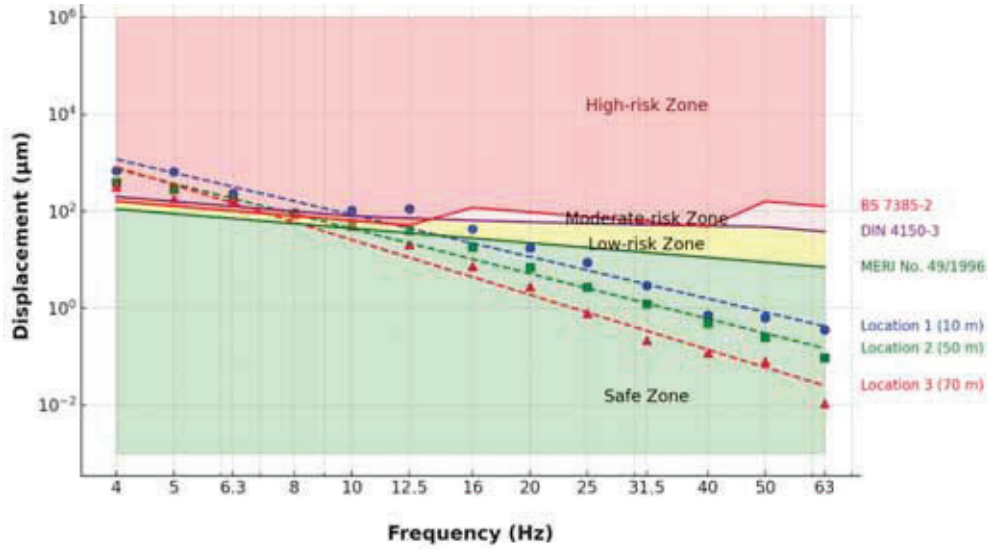

Fig. 8: Graph of particle displacement versus frequency at three observation points (10 m, 50 m, and 70 m) in Kalidengen village, compared against the regulatory limits of MERI No. 49/1996, DIN 4150-3, and BS 7385-2. Risk zones are highlighted: Green (Safe Zone), Yellow (Low-risk Zone), Pink (Moderate-risk Zone), and Red (High-risk Zone)

Indonesian standards.

In contrast, high frequencies (>20 Hz) attenuated rapidly, with safe distances <5 m. Consequently, practical mitigation efforts should aim to decrease low-frequency components via hammer energy adjustments, pre-drilling, or isolation barriers (Kuo *et al.,* 2016).

This condition indicates that the alluvial soils in Kalidengen have a low energy damping capacity for low-frequency waves. Consequently, vibration energy can extend its reach across considerable distances, as demonstrated in Fig. 10. This result is in agreement with prior studies that demonstrate saturated fine-grained soils possess lower attenuation coefficients

compared to those found in sandy or gravelly soils. The effect is most evident at frequencies below 10 Hz (Colaço *et al.*, 2021). In practical terms, mitigation measures should focus on controlling low-frequency components. Alternative techniques such as modifying hammer energy, conducting pre-drilling, or implementing vibration isolation barriers can aid in preventing the surpassing of regulatory thresholds within extensive safe-distance zones (Kuo *et al.*, 2020).

The present results align with earlier findings (Connolly *et al.*, 2016 ; Shamimi Noori et al., 2021) that highlight exponential attenuation in alluvial soils with persistent low-frequency components. The maximum PPV in Kalidengen (20.69 mm/s at 4 Hz, 10 m) exceeded comparable studies, attributed to the high compressibility and moisture content of local soils (Li *et al.*, 2025). Displacement results further

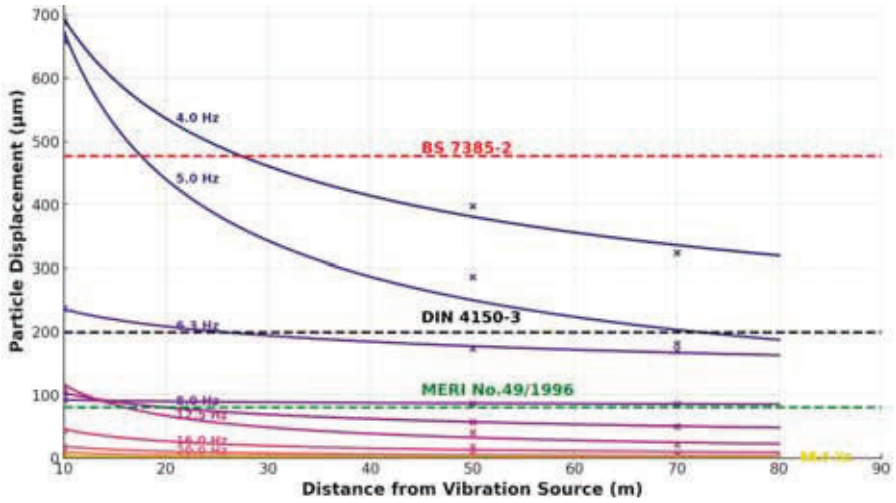

Fig. 9: Figure X. Displacement vs Distance Across Frequencies with Regulatory Limits
Exponential attenuation of particle displacement with distance at various frequencies (4–63 Hz) in Kalidengen Village. Curves represent fitted trends from measurements at 10 m, 50 m, and 70 m, with frequency labels along the curves (10 Hz omitted for clarity). Dashed horizontal lines show regulatory thresholds from BS 7385-2, DIN 4150-3, and MERI No.49/1996, highlighting that lower frequencies induce larger displacements and thus stricter safe distances than higher frequencies.

Table 6: Empirical displacement attenuation equations (µm) across selected frequency ranges and corresponding safe distance estimates (m), based on threshold limits defined in Indonesian regulation (MERI No. 49/1996), German standard (DIN 4150-3), and British standard (BS 7385-2)

Frequency (Hz)	Displacement equation (µm)	MERI No. 49/1996		DIN 4150-3		BS 7385-2	
		Displacement (µm)	Safe distance (m)	Displacement (µm)	Safe distance (m)	Displacement (µm)	Safe distance (m)
4	$2445.93 \times d^{-0.4711}$	100	198.94	477.46	885.6	205.65	32.07
5	$1615.15 \times d^{-0.4611}$	80	159.15	381.97	676.79	152.26	22.8
6.3	$410.53 \times d^{-0.2357}$	70	126.31	303.15	1817.33	148.53	3.62
8	$421.72 \times d^{-0.3881}$	50	99.47	238.73	243.28	41.34	4.33
10	$241.11 \times d^{-0.3681}$	37	79.58	190.99	162.7	20.32	1.88
12.5	$172.20 \times d^{-0.4442}$	32	63.66	152.79	44.2	9.39	1.31
16	$277.34 \times d^{-0.7823}$	25	49.74	119.37	21.67	9	2.94
20	$125.20 \times d^{-0.8284}$	20	39.79	95.49	9.15	3.99	1.39
25	$118.13 \times d^{-1.0922}$	17	31.83	76.39	5.9	3.32	1.49
31.5	$43.52 \times d^{-1.1135}$	12	25.26	60.63	3.18	1.63	0.74
40	$8.55 \times d^{-0.8896}$	8	19.89	47.75	1.08	0.39	0.14
50	$5.42 \times d^{-0.9318}$	8	15.92	38.2	0.66	0.31	0.12
63	$7.79 \times d^{-1.3740}$	6	12.63	30.32	1.21	0.7	0.37

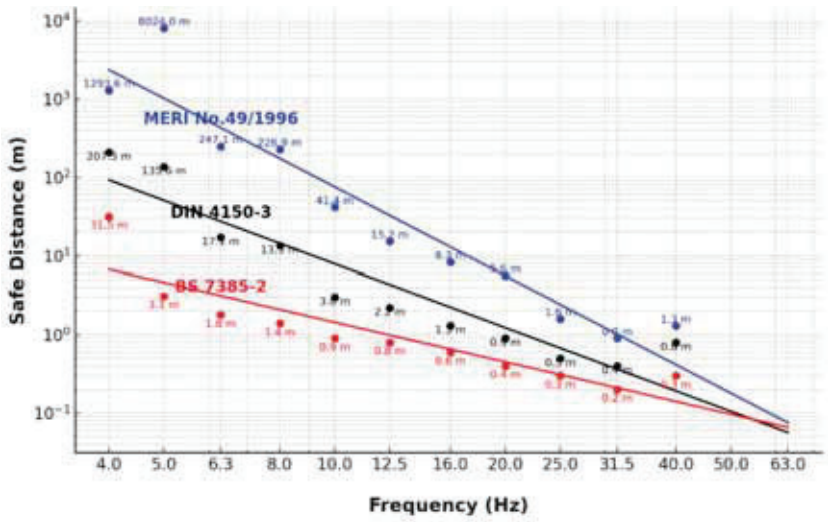

Fig. 10: Safe Distances for Particle Displacement vs Frequency in Kalidengen Village
Log–log regression of safe distance against vibration frequency based on MERI No.49/1996, DIN 4150-3, and BS 7385-2, showing that safe distance decreases with increasing frequency, with MERI being the most stringent.Comparison with previous studies

corroborate the models established by Massarsch and Fellenius (2014), confirming that low-frequency vibrations can cause non-structural damage even at relatively large distances (Musir and Abdul Ghani, 2014). In Table 7, a comparative summary is offered, emphasizing the specific vulnerability of tropical alluvial soils.

There are several limitations in this study that should be taken into account. The monitoring program did not fully consider soil layering, groundwater fluctuations, or seasonal differences between wet and dry periods, even though these factors are known to influence vibration propagation in tropical alluvial soils (Ni *et al.,* 2017; Asnawi *et al.,* 2022). The measurements were also restricted to the hammer energy and pile dimensions used by the contractor, which means that variations in equipment were not evaluated (Karamkar and Adhikary, 2024; Tavasoli and Ghazavi, 2016). Furthermore, vibrations were analyzed in a general context without differentiating the vertical, horizontal, and torsional aspects, each of which can impact structures and human perception differently (Massarsch and Fellenius, 2014; Guo *et al.,* 2023). These limitations illustrate the challenges of performing fieldwork amidst an ongoing infrastructure project (Connolly *et al.,* 2016). Looking ahead, future studies in Indonesia should adopt a broader design that incorporates multiple soil and climate conditions, a wider range of pile-driving equipment, and directional vibration analyses, so that both engineering models and environmental assessments can be improved (Liu and Zhou, 2022). Moreover, this study did not include community-based surveys to directly link measured vibrations with perceptions of comfort, annoyance, or health effects. Subsequent studies ought to merge technical monitoring with socio-environmental assessments to furnish more compelling evidence for urban planners and policymakers (ISO, 1997; Herdiansyah, 2023).

Socio-environmental and *policy implications*

Furthermore, the study reveals significant insights that extend beyond technical aspects, shedding light on the implications for human health, urban development, and ecological governance. The dominant low-frequency vibrations recorded in alluvial soils not only threaten structural safety but also disrupt daily comfort and health in nearby communities (Colaço *et al.,* 2021; Sun *et al.,* 2023). While direct community surveys were not conducted, earlier studies and ISO 2631 standards show that prolonged exposure to vibrations can lead to annoyance, disturbed sleep, and psychosocial stress (ISO, 1997; Herdiansyah, 2023; Silva *et al.,* 2024). These impacts are particularly significant in highly populated areas near infrastructure developments,

Table 7: Comparison of measured vibration characteristics from the present study with selected previous research across different soil types, vibration sources, and regulatory contexts. Parameters include minimum observation distance, maximum peak particle velocity (PPV), dominant frequency ranges, attenuation patterns, and key remarks

Location and soil type	Vibration source	Min. distance (m)	Maximum PPV (mm/s)	Dominant frequency (Hz)	Attenuation pattern	Key remarks	Sources
China – sandy clay alluvium	Diesel hammer	10	15.2	5	Exponential	Rapid decrease after 50 m; PPV < BS threshold at >30 m	Guo *et al.,* 2023
Iran – layered alluvium	Hydraulic piling	8	12.4	6–8	Exponential	High frequencies (>15 Hz) attenuate faster than low frequencies	Ma'hood *et al.,* 2009
Sri Lanka – loose sand (SP)	Falling hammer 5 tons, drop height 3 m	5	15.2	1–80	Affected by soil layers, reflections and refractions	In-fill trench materials can reduce vibration	Jayawardana *et al.,* 2018
Sandy and clayey soils	Hydraulic piling	10	10.8	8	Exponential (with soil improvement)	Soil improvement reduced PPV by up to 40% at <30 m	Kazemzadeh *et al.,* 2023
USA – mixed rock & clay soils	Blasting	5	52	4–10	Exponential	Minor damage observed at PPV 2–5 mm/s (low frequency)	Siskind *et al.,* 1980
Kalidengen Village, Yogyakarta – fine-grained, high-moisture alluvium	Diesel hammer DELMAG D19-42	10	20.69	4–5	Exponential (log–log regression, R^2 > 0.95)	Low-frequency PPV persists over long distances (>800 m at 4 Hz per LH standard)	Present study (2025)

where inhabitants frequently possess few resources to adjust (Connolly *et al.,* 2016). Socio-economic and cultural conditions further shape these responses. Families with modest resources may struggle to repair even minor damage or to relocate temporarily, while cultural attachment to ancestral homes or long-standing neighborhoods can heighten sensitivity to disturbances (Utami *et al.,* 2023). Such circumstances underscore the necessity of including local context in the assessment of vibration risks. Attention must also be given to critical facilities such as schools, hospitals, and utilities. Even moderate vibrations can disrupt learning, interfere with sensitive medical equipment, or affect essential public services (WHO, 2018). Even though these facilities were not evaluated directly in this context, they ought to be incorporated into future evaluations to ensure more thorough guidance for secure urban development. In addition, vibrations are rarely an isolated issue. Pile-driving and similar activities often generate secondary impacts like dust and noise, which together intensify community discomfort (Kuo *et al.,* 2020). A comprehensive environmental evaluation that integrates vibration, noise, and air quality is thus advised. From a regulatory perspective, the current Indonesian vibration standard (MERI, 1996) may not adequately reflect risks in tropical alluvial environments, since it is largely adapted from stiffer soil contexts. Differences observed between Indonesian, German (DIN 4150-3), and British (BS 7385-2) standards underscore the need for harmonization and local recalibration to protect vulnerable groups (DIN 4150-3, 1999; BS 7385-2, 1993). As an illustration, structural damage thresholds may seem to be adequate, yet human

comfort thresholds can frequently be surpassed at distances of up to 60 m from the source (Ekman *et al.,* 2021). This suggests that regulations should adopt dual criteria, covering both structural safety and human comfort (Colaço *et al.,* 2022). Economically, applying large buffer zones is unrealistic in dense settlements, which makes cost-effective strategies—such as pre-drilling, the use of vibratory or pressed-in piles, and temporary isolation barriers—more practical (Shao *et al.,* 2023 ; Toygar and Ulgen, 2021). Approaches to adaptive management, which involve real-time monitoring to alter hammer energy or construction timelines, can effectively lower risks, boost community acceptance, and reduce disagreements over compensation (Connolly *et al.,* 2016). Recent advances have also proposed simplified tools to expedite pile-driving vibration assessment, which can support decision-making during ongoing construction (Abouelmaty *et al.,* 2025). Anticipating the future, climate change might add complexity to vibration behavior, since variations in groundwater levels and soil moisture could modify attenuation patterns, heightening risks in particular seasons (Asnawi *et al.,* 2022). Sustainable urban planning should therefore incorporate vibration risk corridors into zoning and land-use regulations, ensuring that schools, hospitals, and other sensitive facilities are located at safer distances from major projects (Lin *et al.,* 2024). Addressing vibration as an environmental pollutant ultimately requires interdisciplinary collaboration between engineers, environmental scientists, urban planners, and public health experts. Such collaboration is the only way to safeguard both the structural integrity and the well-being of the community (Dong *et al.,* 2025). These socio-environmental considerations reinforce the urgency of updating Indonesia's vibration regulations to include explicit human comfort criteria (Avci *et al.,* 2020) alongside structural safety thresholds (Caro-González *et al.,* 2023 ; Kurniawan *et al.,* 2020; MERI, 1996 ; Park *et al.,* 2025; Romianingsih *et al.,* 2023).

CONCLUSION

This study has delivered an extensive empirical analysis of ground vibrations produced by diesel-hammer pile driving in tropical alluvial soils, particularly highlighting their significance for both structural integrity and environmental sustainability. Systematic field monitoring at three observation points (10 m, 50 m, and 70 m) revealed that vibration energy was largely concentrated in the low-frequency domain of 5–15 Hz, overlapping with the natural frequencies of single-storey masonry dwellings that dominate many coastal and peri-urban settlements in Southeast Asia. At a distance of 10 m, the observed PPV measured 5.6 mm/s, which not only went beyond the generally accepted human comfort threshold of 0.3 mm/s but also exceeded the cosmetic damage threshold of 2.0 mm/s. This confirms that pile driving can lead to noticeable discomfort and the potential for structural damage, even at shorter offsets. Although PPV attenuated to 1.8 mm/s and 1.2 mm/s at 50 m and 70 m respectively, the derived power-law exponent of 1.12 indicates that the decay rate in saturated alluvial sediments remains relatively slow, allowing vibrations to persist over considerable distances. Comparison with international and national standards, including DIN 4150-3 (Germany), BS 7385-2 (UK), and the Indonesian MERI No. 49/1996, highlighted a critical discrepancy between structural safety limits and human comfort criteria. Even though structural damage is improbable past 50 m, the discomfort levels experienced by nearby residents in the vicinity were still surpassed at the most distant observation point of 70 m, indicating that actual comfort thresholds could extend well beyond this range. This discrepancy underlines the importance of integrating both engineering safety margins and community-based environmental criteria in the evaluation of construction vibrations. These results confirm that tropical alluvial soils amplify low-frequency components more effectively than the more rigid soils usually recorded in temperate regions. As a consequence, vibration standards and mitigation strategies cannot simply be transferred from European contexts but require local adjustment. Practical implications include the adoption of context-specific buffer zones and adaptive mitigation strategies to reduce community exposure. This study contributes to the scientific knowledge of frequency-specific attenuation characteristics in tropical alluvial soils, an area that lacks sufficient empirical data. By integrating PPV, displacement, and frequency analyses and cross-validating with multiple standards, the research bridges geotechnical vibration analysis with environmental and social impact assessment. The framing of construction-induced vibrations as a form of environmental pollution expands the

scope of vibration research from purely engineering safety considerations toward the broader domain of environmental management and sustainable urban development. The study also reveals that the present Indonesian vibration regulations (MERI 1996) are still inadequate for ensuring human comfort in soft alluvial soils. It is crucial to harmonize with international standards, making vibration impact assessments a necessary part of AMDAL for large infrastructure initiatives. Achieving these reforms requires interdisciplinary collaboration among engineers, environmental scientists, urban planners, and public health experts to ensure sustainable and socially responsible development. Furthermore, future studies should complement technical evaluations with direct community surveys to better capture socio-cultural responses and public health impacts, thereby strengthening the link between technical data and lived experience.

AUTHOR CONTRIBUTIONS

A. Margiantono conceived and designed the study, conducted the field monitoring, carried out data analysis and interpretation, and prepared the initial draft of the manuscript. E. Setiawati contributed to data processing, assisted in the interpretation of results, and critically revised the manuscript draft.

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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.

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ABBREVIATIONS

%	Percent
µm	Micrometer
AI	Artificial intelligence
BS	British Standard
DIN	Deutsches Institut für Normung
EIA	Environmental Impact Assessment
Eq.	Equation
FFT	Fast Fourier Transform
Hz	Hertz
kg	Kilogram
kNm	Kilonewton meter
MERI No. 49/1996	Indonesian Ministry of Environment Decree No. 49/1996
m.	Meter
Min.	Minute
mm	Millimeter
mm/s	Millimeters per second
m/s	Meters per second

PPV	Peak particle velocity
RTS	Real-time system
SARA	Seismic and Acoustic Remote Analyzer
YIA	Yogyakarta International Airport

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CASE STUDY

Strategic sustainability assessment of rural agribusiness infrastructure systems in humid tropical regions

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ABSTRACT

BACKGROUND AND OBJECTIVES: Agribusiness infrastructure systems play a pivotal role in rural transformation by strengthening local economies, reducing post-harvest losses, and advancing sustainable food supply chains. In the context of the global development agenda, their significance is directly associated with sustainable development goals, especially in fostering food security, alleviating poverty, and encouraging environmentally sustainable practices. Despite this significance, empirical evidence on their long-term sustainability in humid tropical regions remains limited, leaving policymakers without comprehensive guidance for effective interventions. This study tackles the existing gap by assessing the multifaceted sustainability of agribusiness distribution systems and developing strategic approaches for their enhancement.
METHODS: A multidimensional scaling technique, consistent with the sustainability assessment framework of food and agriculture systems, was utilized to evaluate the economic, social, environmental, technological, and institutional dimensions. Data collection involved stakeholder surveys, expert evaluations, and field observations, with robustness tested using Monte Carlo simulations. Leverage analysis was used to identify influential attributes, while strategic options were crafted using the strengths, weaknesses, opportunities, and threats framework. A case study was conducted on a rural agribusiness sub-terminal in West Java, Indonesia, to illustrate the framework.
FINDINGS: The evaluation categorized the system as having low sustainability, with total scores falling below 50 percent. The lowest performances were observed in the technological (29.33 percent) and economic (34.61 percent) dimensions, followed by environmental (42.07 percent) and institutional (43.76 percent) aspects. Social performance was comparatively stronger, though it remained moderate. The leverage analysis highlighted financial access, digital innovation, and emission reduction as critical factors. Strategic analysis highlighted opportunities in fintech adoption, clean technologies, and multi-stakeholder collaboration, while main threats included climate risks, regulatory uncertainty, and market volatility.
CONCLUSION: The study proposes an integrated strategic framework across eight domains: financial empowerment, market stability, social inclusion, community strengthening, environmental management, technology adoption, governance, and institutional collaboration. The framework provides valuable insights that can be applied to improve agribusiness distribution systems in humid tropical areas and offers a replicable guide for planning sustainable rural infrastructure. Methodologically, it demonstrates the novelty of combining multidimensional scaling with strengths, weaknesses, opportunities, and threats framework to bridge diagnostic assessment and strategic design, offering both theoretical and policy-relevant contributions.

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INTRODUCTION

The sustainability of agricultural systems is a vital issue in the global development agenda, especially as the world confronts growing challenges like as climate change, land degradation, biodiversity loss, and increasing demand for food (Adams *et al.*, 2025). According to the Food and Agriculture Organization (FAO), nearly one-third of global agricultural land is degraded, while the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2022) highlights that agriculture contributes about 21–24 percent (%) of total greenhouse gas emissions, primarily from land-use change and production practices. These pressures highlight the critical necessity of transforming agricultural systems to ensure food security, protect ecosystems, and promote equitable development (Rehman *et al.*, 2022). Well-managed agricultural systems can simultaneously meet rising food demand, support rural livelihoods, and mitigate environmental degradation. Within the framework of the United Nations Sustainable Development Goals (SDGs), sustainable agriculture plays a pivotal role in achieving food security, poverty reduction, and environmental protection (Zarbà *et al.*, 2025). Countries in the Global South, such as Indonesia, face a dual challenge in agricultural sustainability: the need to boost food production to meet the demands of a growing population while also using natural resources in an efficient manner. These nations are significantly impacted by climate change, land degradation, and unsustainability, yet they persist in striving for productivity and economic growth alongside long-term sustainability (Dharmayanti *et al.*, 2023). Indonesia, as a representative humid tropical country with vast agricultural resources and biodiversity, illustrates this complexity and holds significant potential to contribute to global food security (Borelli *et al.*, 2024). The escalation of farming practices has resulted in soil degradation, reduced water availability, and deforestation, posing risks to both ecosystems and climate stability (Kaushal *et al.*, 2025). Strengthening agricultural value chains through agribusiness sub-terminals (ASTs) offers a pathway to balance productivity with sustainability, as ASTs can improve market connectivity, reduce post-harvest losses, and enhance opportunities for smallholder farmers (Febrimeli *et al.*, 2022). As key strategic nodes, ASTs are instrumental in driving economic growth while ensuring and environmental sustainability (Amamou *et al.*, 2025). However, their potential is often undermined by underutilization, poor maintenance, and weak governance, which limit access to wider markets and reduce their capacity to add value (Padangaran *et al.*, 2025). The absence of strategic coherence and institutional inefficiencies further constrain services including finance, training, and market information. Despite their importance, few studies have conducted comprehensive sustainability assessments of ASTs. Studies to date has largely concentrated on specific components like infrastructure or market access, but infrequently adopts a holistic, multidimensional viewpoint that spans economic, ecological, social, technological, and institutional dimensions. In sustainability studies, multidimensional scaling (MDS) has been widely employed to evaluate diverse agricultural systems. Previous applications include composting agricultural waste (Santoso *et al.*, 2023), duck production (Bakrie *et al.*, 2023), rice cultivation (Rachman *et al.*, 2022), cattle production (Rohaeni *et al.*, 2024), sago-based feed production (Allaily *et al.*, 2024), waste management (Ismail *et al.*, 2025), and integrated farming (Widjaja *et al.*, 2024). These investigations showcase the flexibility of MDS in encapsulating complex sustainability features across diverse commodities and environments. Yet, few if any have applied MDS to assess agribusiness sub-terminals in humid tropical regions. Furthermore, while strengths–weaknesses–opportunities–threats (SWOT) analysis is commonly used for strategy formulation, its integration with MDS remains rare in this context, limiting the ability to translate diagnostic results into actionable interventions. This gap creates obstacles for policymakers and practitioners when attempting to devise effective measures to enhance system sustainability. This study addresses that gap by applying MDS to assess the sustainability of agribusiness distribution systems. The framework is adapted from the Food and Agriculture Organization's Sustainability Assessment of Food and Agriculture Systems (SAFA), which emphasizes a balance among economic viability, environmental protection, social equity, and institutional governance (Wadghane *et al.*, 2025). Sustainability scores are derived from survey data, expert evaluations, and field observations across the five dimensions. Monte Carlo simulations are applied to test robustness, while leverage analysis identifies attributes most critical to

system performance. To complement this, a SWOT analysis is employed to design strategic responses tailored to contextual realities (Dergan *et al*., 2022). Considering this context, the purpose of this study is to analyze the multifaceted sustainability of agribusiness sub-terminals in West Java, Indonesia, utilizing an integrated MDS–SWOT framework, and to recommend strategic actions that bolster resilience and support long-term sustainability. Two guiding research questions structure the analysis: i). What is the current sustainability status of AST Cigombong across economic, social, environmental, technological, and institutional dimensions? ii). Which leverage factors and strategies are most critical to enhancing sustainability in humid tropical agribusiness systems? The current study makes two key contributions. Conceptually, it improves sustainability assessment techniques by integrating MDS with SWOT, delivering a consistent framework that combines diagnostic evaluation with strategic planning. Practically, it generates actionable insights for policymakers and practitioners to design interventions that strengthen ASTs in Indonesia and other humid tropical regions. Furthermore, the insights gained from the West Java case study extend to broader applications, offering valuable knowledge for refining agribusiness distribution systems, boosting the incomes of smallholders, and fostering eco-friendly practices. By integrating multidimensional assessment with strategic design, this research underscores the importance of resilient agribusiness infrastructures as pathways toward sustainable rural development. The long-lasting viability of agribusiness infrastructures in humid tropical zones is heavily impacted by fluctuations in climate and severe weather occurrences. Heavy rains, floods, or heatwaves can reduce drying efficiency, accelerate post-harvest losses, and damage physical



Fig. 1: Geographical location of the study area in Cianjur Regency of West Java Province, Indonesia (a: Cianjur Regency, West Java; b: Agribusiness sub-Terminal at Cianjur regency; c: Vegetables from farmers in Agribusiness Sub-Terminal)

assets, increasing costs and reducing reliability. To address this, infrastructures require climate-adaptive designs such as modular, flood-resilient facilities and hybrid energy systems that enhance resilience and maintain performance under variable conditions. This study was conducted by the Research Center for Agroindustry, at the National Research and Innovation Agency, Indonesia, during the period 2024 to 2025.

MATERIALS AND METHODS

Study area

The study was conducted in Cigombong sub-district, Cianjur Regency, West Java, located about 90 km southeast of Jakarta (Fig. 1). Cigombong STA is strategically located near the Jakarta–Bogor market corridor, serves thousands of smallholder farmers, and has relatively complete facilities (grading, packaging, storage, and logistics) which, although underutilized, make it one of the most representative agribusiness sub-terminals in West Java. The landscape is distinguished by its productive farmland that cultivates rice, corn, horticultural products, and livestock, and it is conveniently situated in proximity to major cities. Cigombong hosts a key ASTs that aggregates, processes, and distributes agricultural products, supported by storage, processing, and logistics facilities (Fig.2). This hub links local farms to both regional and national markets, making Cigombong as a key location for evaluating the sustainability of agro-industrial systems in Indonesia. Comparative profiles of Cigombong AST with other hubs are presented in Table 1.

Data collection and analysis

This study combined primary and secondary data to assess the sustainability of agribusiness practices in Cigombong. Primary data were collected through field observations, in-depth interviews, and a focus group discussion (FGD) with eight purposively selected experts, including farmer leaders, sub-terminal managers, government officials, traders, academics, financial institutions, and sustainability practitioners. Every participant possessed a minimum of five years of pertinent experience and occupied strategic roles, which guaranteed contextually rich insights and triangulation across operational, policy, financial, and academic viewpoints (Memon *et al.*, 2025). Secondary data were obtained from literature, policy documents, and reports on agribusiness sustainability. The sustainability assessment applied



Fig. 2: Supply chain flow of agribusiness sub-terminals: from farmers to consumers

Table 1: Profile of ASTs in Indonesia and comparative international food hubs.

Key aspect	AST Cigombong, Indonesia (Case study)	AST Pulang Pisau, Indonesia (Anugrah and Dewi, 2021)	Tamil Nadu Food Hub, India (Marimuthu, 2025)	Food Terminal Inc. (FTI), Philippines (Digal *et al*., 2024)
Number of facilities	1 unit (Cianjur District, West Java)	1 unit (Central Kalimantan)	>15 regional hubs	1 major terminal (Metro Manila)
Main commodities	Rice, maize, vegetables (chili, tomato, cabbage)	Vegetables and tropical fruits	Vegetables, flowers, dairy	Fruits, vegetables, meat, fish
Farmers involved	~2,500 smallholder farmers	~1,200 farmers	~10,000 smallholders	~5,000 farmers and traders
Main services	Aggregation, storage, grading, packaging, distribution	Storage and auction market	Aggregation, cold storage, logistics, e-commerce	Wholesale distribution, cold storage, auctions
Market orientation	Local (Cianjur, Bogor), regional (Jakarta)	Local and regional	Domestic urban markets	Metro Manila and export markets
Supporting infrastructure	Warehouses, limited cold storage, grading and packaging units, road transport	Warehouse, auction facilities	Modern cold storage, logistics hubs, digital marketplace	Large-scale cold storage, wholesale trading halls

the rapid appraisal for fisheries (RAPFISH) method within a MDS framework, covering economic, social, environmental, technological, and institutional dimensions (Anjaria, 2022). A structured questionnaire was developed with thirty-one attributes that utilized a 5-point Likert scale for ratings. This expert-oriented methodology focused on the weighted interpretation of sustainability performance, which makes it ideal for exploratory assessments within intricate agribusiness frameworks. Data from expert assessments were processed through MDS to generate a composite sustainability index and profile for the AST. To ensure robustness, Monte Carlo simulations were employed to validate the reliability of results (AL-agele *et al.,* 2021). This ongoing examination reinforced confidence in the outcomes and equipped policymakers with a comprehensive perspective on sustainability aspects, facilitating the creation of strategies aimed at boosting the resilience of agribusiness systems and steering future advancements in Indonesia's agro-industrial domain.

Agribusiness sustainability analysis

The sustainability performance of AST Cigombong was evaluated using MDS scores categorized into four levels (Table 2). Scores of 0–25% indicate "Poor" (unsustainable), 25.01–50% "Less Sustainable," 50.01–75% "Fairly Sustainable," and above 75.01% "Good" (very sustainable). Each level reflects increasing strength in economic, environmental, and institutional dimensions, with higher scores serving as benchmarks for replication.

Classifying sustainability into distinct tiers allows stakeholders to pinpoint key focus areas and distribute resources appropriately, thereby bolstering strategies that improve the viability of agribusiness sub-terminals in rural Indonesia and beyond. The ordination process applies to the alternating least squares scaling (ALSCAL) algorithm, a common MDS method that minimizes discrepancies between observed and modeled data, quantified by s-stress, to improve accuracy of representation. The Euclidean distance, which represents the dissimilarity between two objects, using Eq. 1 (Pitcher and Preikshot, 2001):

$$d = \sqrt{\left(\left|x_1 - x_2\right|^2 + \left|y_1 - y_2\right|^2 + \left|z_1 - x_2\right|^2 + \ldots\right)} \quad (1)$$

Where, d denotes the Euclidean distance between two points in n-dimensional space; x_1, y_1, z_1 and x_2, y_2, z_2 represent the coordinates of the two objects on each dimension;

Table 2: Sustainability index categories and status for each dimension.

No.	Index range (%)	Classification	Sustainability status
1	0 – 25	Poor	Unsustainable
2	25.01 – 50	Less	Less Sustainable
3	50.01 – 75	Quite	Fairly Sustainable
4	75.01 – 100	Good	Very Sustainable

and the ellipsis, indicates the continuation of dimensions beyond the third (for higher-dimensional spaces). Within the framework of MDS, this distance functions as a primary indicator of dissimilarity among the objects under comparison. In the context of MDS, the positioning of objects or points is determined by analyzing the Euclidean distance (d_{ij}) between two points (*I* and *j*) and comparing it to a reference or fitted distance (o_{ij}), using Eq. 2 (Pitcher and Preikshot, 2001):

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (2)$$

Where, α is the intercept or constant term, β is the regression coefficient describing the relationship between the observed distance (d_{ij}) and the fitted or model distance (δ_{ij}), and ε is the error term capturing deviations between observed and predicted distances. This regression strategy is included in the ALSCAL algorithm, which continuously refines object positions to reduce discrepancies. The ALSCAL algorithm is the regression method utilized in this process. This strategy focuses on improving the squared Euclidean distance (dijk) concerning the squared data (origin=oijk), with modifications taking place in a three-dimensional space. The model's fit is quantified by the S-Stress statistic, using Eq. 3 (Pitcher and Preikshot, 2001):

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (3)$$

Where, *s* denotes the S-Stress value indicating the level of discrepancy between observed and modeled distances; d_{ijk} is the computed Euclidean distance between objects i and j in the kth dimension; o_{ijk} represents the corresponding original or input distance; *m* is the number of dimensions considered and *i*, *j* are object indices. A smaller value indicates a better ordination fit, reflecting a more accurate representation of the dissimilarity structure. In this equation, the squared distance signifies the Euclidean distance, which is allocated a distinct value for each pair of points, thereby enhancing calculation and optimization in the ordination. The squared Euclidean distance is expressed using Eq. 4 (Pitcher and Preikshot, 2001):

$$d_{ijk} = \sum_{a=1}^{r} w_{ka}\left(x_{ia} - x_{ja}\right)^2 \quad (4)$$

Where, d_{ijk} denotes the squared distance between objects *i* and *j* along dimension *k*; x_{ia} and x_{ja} represent the coordinate values of objects *i* and *j* on attribute or axis *a*; w_{ka} is the weighting factor assigned to dimension a under the kth configuration; and *r* represents the total number of attributes or dimensions.

Leverage factor and validity assessment

Leverage factor values fall within a range of 2% to 8%, indicating a moderate to strong impact on sustainability. Leverage values that fall below 2% are seen as having minimal effect, while those that go beyond 8% are classified as dominant, reflecting their significant importance in sustainability. Table 3 presents the factors identified as influential and dominant in the analysis.

Monte Carlo simulation is employed to quantify uncertainty in MDS results by determining the error margin. To assess the reliability of the sustainability index, stochastic variations were incorporated into the score matrix, and then 25 random simulation iterations were conducted. This method allows for an evaluation of the sensitivity of the MDS outcomes and the statistical reliability of the sustainability classifications. If the difference between the MDS and Monte Carlo results is small (under 5%), it suggests

Table 3: Leverage factor parameter values

No.	Factor Value (%)	Category	Description
1	< 2	Neutral	Not influential
2	2 – 8	Influential	Moderate-to-good impact
3	> 8	Significant	Dominant

that the MDS analysis offers a reliable sustainability assessment with 95% confidence (Asrol *et al.*, 2024). Additionally, the robustness of MDS outcomes in the face of weight changes highlights the potential impact of alternative weighting schemes, which could lead to slight modifications in the absolute index values.

Integration of MDS, SWOT analysis, and deductive thematic mapping

In this study, a SWOT framework was employed to transform significant attributes recognized through MDS into implementable strategies (Alfadillah *et al.*, 2024). Internal factors were extracted from leverage attributes across the economic, social, environmental, technological, and institutional dimensions, while external factors were gathered from policy documents, literature, and consultations with stakeholders. These were aligned in a SWOT matrix to generate Strengths – Opportunities (SO), Weaknesses – Opportunities (WO), Strengths – Threats (ST), and Weaknesses – Threats (WT) strategies, extending the analysis beyond diagnostics to practical policy guidance. In addition, deductive mapping was employed to cluster SWOT-derived strategies into thematic domains, ensuring coherence and addressing systemic sustainability challenges. This integration of MDS, SWOT, and deductive mapping signifies a groundbreaking contribution, presenting both precise diagnostics and a transferable strategy for improving agribusiness sub-terminals and related rural infrastructures.

RESULTS AND DISCUSSION

Key attributes in AST operational

The FGD identified five critical sustainability dimensions—economic, social, environmental, technological, and institutional as a framework for evaluating agribusiness sub-terminals (Table 4). The economic facet involves cost efficiency, price stability, and the availability of services and financing, which are crucial for resilience and the well-being of farmers (Kumar *et al.*, 2020). Social sustainability focuses on welfare, stakeholder involvement, and equitable participation, ensuring fairness, reducing conflict, and supporting long-term acceptance of agribusiness practices (Rushchitskaya *et al.*, 2024). Attributes related to the environment, including waste management, emission control, and water conservation, support worldwide goals by decreasing ecological impacts (Alvarez-Ochoa *et al.*, 2024). The technological dimension emphasizes infrastructure, innovation, and product safety through traceability and training (Latino *et al.*, 2024). In conclusion, the sustainability of institutions is contingent upon effective governance and regulations that facilitate continuous support for sustainable practices (Nartey, 2024). In combination, these five dimensions present an all-encompassing viewpoint for measuring the performance and enduring sustainability of agribusiness sub-terminals in Indonesia.

Index of sustainability

Fig. 3 illustrates the RAPFISH circular ordination graphs of AST Cigombong, showing sustainability across economic, social, environmental, technological, and institutional dimensions. The graphs highlight areas of strength and weakness through GOOD and BAD indicators, while anchors and UP/DOWN values reveal the direction of improvement needed. Findings reveal a persistent low performance in every dimension, validating the earlier designation of "less sustainable"(Nasir *et al.*, 2024). Table 5 summarizes the index scores and data quality metrics. The economic (34.61%) and technological (29.33%) dimensions scored the lowest, with other dimensions also below the sustainability threshold. High R-squared and low stress scores validate the analysis's robustness, notwithstanding the low values. Monte Carlo simulations further confirm reliability, showing only small differences with the primary index (Sadad *et al.*, 2022). These conclusions underscore the pressing requirement for specific measures to bolster sustainability in every aspect.

Fig. 4 presents the radar chart of AST Cigombong's

Table 4: Dimensions and attributes of agribusiness sustainability assessment

Dimension		Attributes
Economic	1.	Operational cost efficiency
	2.	Agricultural product price stability
	3.	Accessibility of services for farmers
	4.	Improvement of farmers' income
	5.	Value addition to agricultural products
	6.	Facilitation of financing access for farmers
Social	1.	Social welfare of stakeholders
	2.	Stakeholders' participation
	3.	Working conditions
	4.	Social relations
	5.	Gender equality
	6.	Human resource development programs
Environmental	1.	Waste management
	2.	Emission and pollution control
	3.	Water management
	4.	Energy efficiency
	5.	Availability of green open spaces
	6.	Environmental education
Technological	1.	Technology infrastructure
	2.	Technology adoption and innovation
	3.	Technology for product traceability and food safety
	4.	Human resource training and capacity
	5.	Transportation and distribution
	6.	Technology for increasing productivity
Institutional	1.	Institutional structure
	2.	Availability and effectiveness of regulations
	3.	Management performance
	4.	Support from government and related institutions
	5.	Access to information and public services
	6.	Monitoring and evaluation system
	7.	Transparency

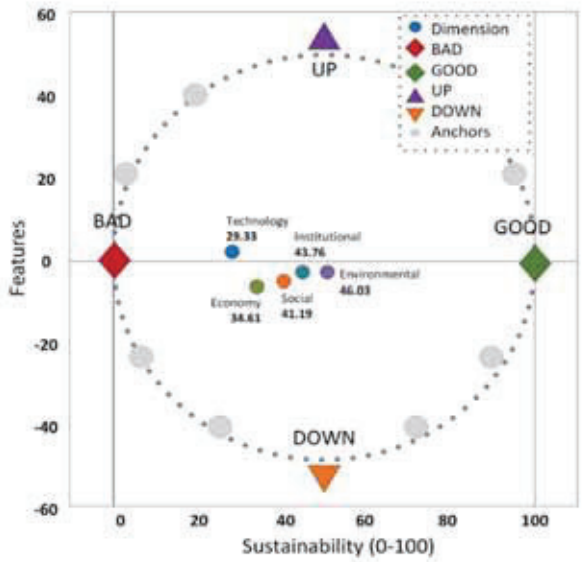

Fig. 3: RAPFISH circular ordination of sustainability index scores for the Agribusiness Sub-Terminal in Cianjur across five dimensions

Table 5: Summary of sustainability index scores and associated data quality levels

Dimension	Index	Stress	R-squared	Monte Carlo Simulation	Index Difference	Status
Economy	34.61	0.0993	0.9901	34.38	0.23	Less Sustainable
Social	41.19	0.0993	0.9901	41.04	0.15	Less Sustainable
Environmental	42.07	0.1004	0.9899	42.14	0.07	Less Sustainable
Technology	29.33	0.0997	0.9901	29.32	0.01	Less Sustainable
Institutional	43.76	0.1031	0.9894	43.83	0.16	Less Sustainable
Average	38.19					Less Sustainable

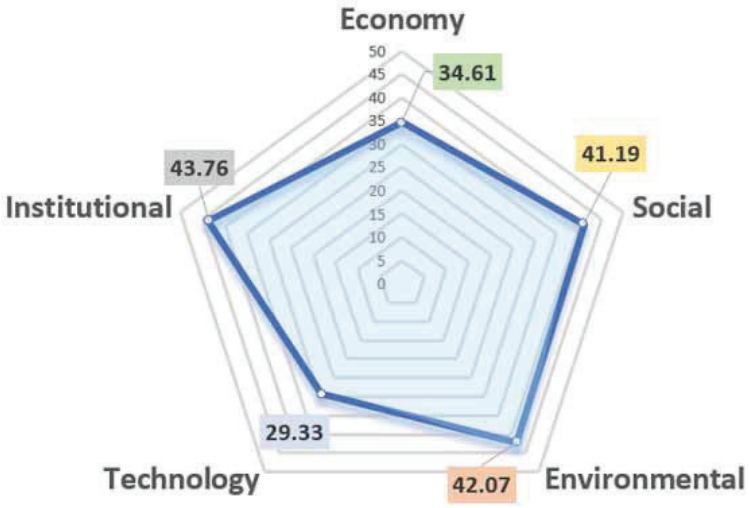

Fig. 4: Radar chart showing sustainability index of AST Cigombong across five dimensions: economy, social, environmental, technology, institutional.

sustainability scores across five dimensions. Results show no dimension reaches sustainability, with the lowest scores in economic (34.61%) and technological (29.33%) aspects, while environmental (42.07%) and institutional (43.76%) perform relatively better. These variations highlight priority areas for intervention to strengthen overall sustainability.

Economic dimension

The economic sustainability of AST Cigombong is weak, with an index of 34.61%, categorized as less sustainable (Fig. 5). The accessibility of farmer services and the efficiency of operational costs (RMSD 3.68%) are two vital factors that prevail in this dimension. Limited access to financial services constrains smallholder productivity, as income, land size, and experience directly affect credit availability (Purwanti *et al.*, 2023). Vulnerabilities in profitability, capital structures, and input costs further threaten stability. Embracing technological advancements, such as renewable energy and artificial intelligence, has the potential to enhance efficiency and lower expenses (Ragazou *et al.*, 2022). Strengthening infrastructure, improving services, and managing costs are essential to enhance economic resilience (Anggriani *et al.*, 2019). Conceptually, the low economic (34.61%) and technological (29.33%) scores are consistent with persistent challenges in rural income growth and post-harvest loss reduction, even though direct statistical correlations were not tested in this study.

Social dimension

The MDS analysis revealed that the social sustainability index of the AST is 41.19%, indicating a less sustainable status, supported by a high goodness-of-fit (R^2 = 0.9901) and low stress value



Fig. 5: Leverages of attributes for economic dimension

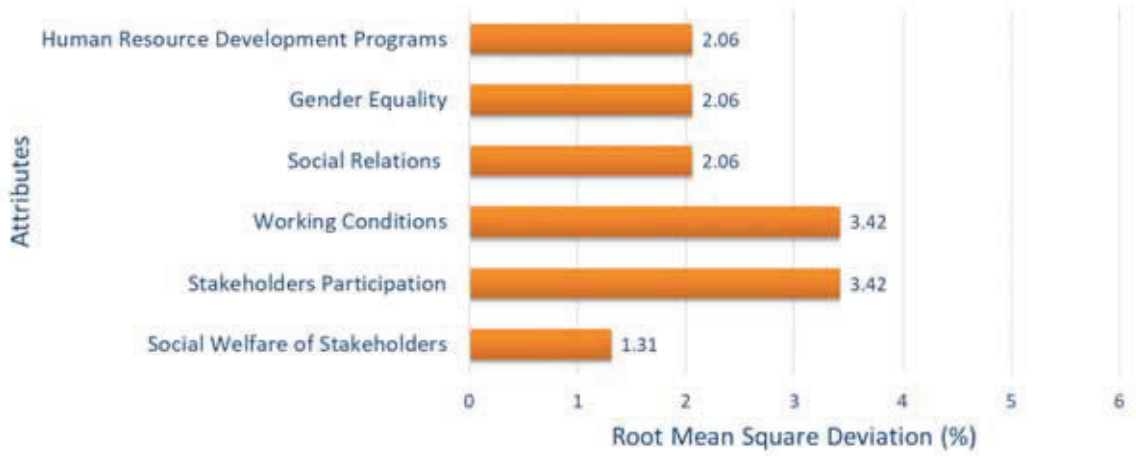

Fig. 6: Leverages of attributes for social dimension

(0.0993%). Key factors impacting social sustainability include stakeholder participation (3.42%), working conditions (3.42%), social relations (2.06%), and gender equality (2.06%), with social welfare (1.31%) being relatively neutral. In spite of some engagement from stakeholders, the integration of broader social equity and welfare is still inadequate for achieving sustainability (Fig. 6). High leverage values for stakeholder participation and working conditions highlight their significant influence on social sustainability, as effective decision-making and fair labor conditions are essential for agribusiness governance (Kotir *et al*., 2024). Recent studies emphasize the significance of social capital in promoting resilience, as demonstrated in the agroforestry systems of North Luwu and the Tengger highlands, where networks based on trust and active engagement have fostered cooperation and sustainable practices (Yusriadi, 2025). To address these gaps, technical and strategic interventions are needed, including institutionalizing multi-stakeholder platforms, participatory planning, and compliance with International Labor Organization (ILO) standards to improve working conditions (Kilelu *et al.*, 2017). Moreover, strengthening gender equality by means of empowerment initiatives, training opportunities

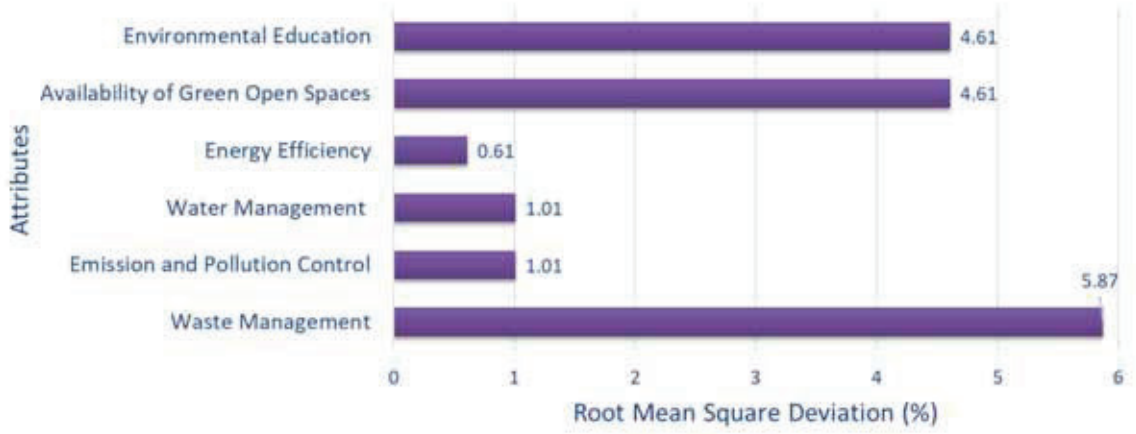

Fig. 7: Leverages of attributes for environmental dimension

for women farmers, and enhanced access to financial services is vital for promoting inclusivity (Kaine and Wright, 2022). These measures will foster better trust, collaboration, and ultimately, improved sustainability outcomes in agribusiness value chains.

Environmental dimension

The environmental sustainability of AST Cigombong scored 42.07%, categorized as less sustainable, though supported by strong statistical reliability (R^2 = 0.9899; Stress = 0.1004). Key weaknesses include waste management, environmental education, and green open space (Fig. 7).

The results show that environmental considerations are not as advanced as the economic and technological sectors. Beyond its economic and technological performance, the Cigombong AST demonstrates significant environmental implications that directly affect its sustainability trajectory. Weaknesses in waste management, emission reduction, and green open space utilization highlight the urgent need for ecological improvements. Strengthening these components aligns the sub-terminal not just with agribusiness efficiency but also with wider environmental goals including pollution control, biodiversity safeguarding, and climate adaptability. Integrating circular economy strategies like composting organic waste, utilizing clean technology for storage and distribution, and minimizing energy consumption can improve ecological outcomes while also promoting the sustainability of agribusiness in the long run. By positioning environmental management as a core strategic pillar, the Cigombong case clearly connects agribusiness sustainability with the journal's broader environmental focus (Springmann *et al*., 2018). Waste management (5.87%) was the most influential factor, with organic waste from spoiled produce and market activities posing ecological risks (Reddy *et al.*, 2025). Solutions such as composting, animal feed conversion, and reducing plastic use can improve outcomes. Evidence from Indonesian coffee hubs shows that efficient water use, reduced processing waste, and lower logistics emissions enhance sustainability (Parmawati *et al.*, 2023). Integrating circular economy principles, resource recycling, and clean technologies is essential for long-term resilience (Bazienė *et al*., 2024). Policy incentives linking environmental standards with market access could accelerate adoption of green innovations. Placing emphasis on waste management, resource efficiency, and renewable energy will lead to a reduction in environmental impacts and an increase in AST's sustainability. This result shows that the ecological aspects of the agribusiness sub-terminal are weaker and need greater attention. Key leverage points include emissions from diesel-based logistics, which call for cleaner energy adoption and land use pressures that may threaten soil and watershed stability (Ghomi *et al*., 2023). While direct measurements were not performed, coordinating improvements with emission reduction and sustainable land use will enhance the ecological dimension and promote long-term sustainability.

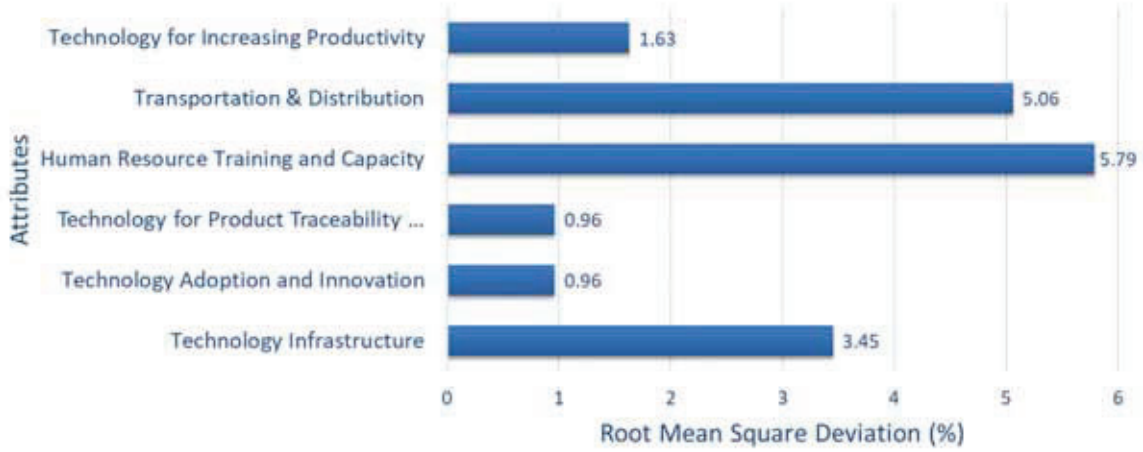

Fig. 8: Leverages of attributes for technology dimension

Technological dimension

AST Cigombong's technology sustainability index is 29.33%, categorized as less sustainable but statistically reliable (R^2 = 0.9901; Stress = 0.0997). Major weaknesses include human resource training (5.79%), transportation and distribution (5.06%), and technology infrastructure (3.45%), which constrain competitiveness and food safety standards (Fig. 8). Limited investment in infrastructure and skills hinders modernization and market opportunities. To fill these gaps, it is essential to implement automation, traceability enabled by the Internet of Things (IoT), smart packaging, and data-driven decision-making to enhance supply chains and elevate quality (Du *et al*., 2025). Expanding training programs and digital infrastructure should be prioritized, with policy support for innovation subsidies and infrastructure development. Closing these gaps will enhance AST's technological sustainability and strengthen the resilience of Indonesia's agribusiness sector (Tulungen *et al*., 2025).

Institutional dimension

The institutional sustainability index of AST Cigombong is 43.76%, categorized as less sustainable but statistically valid (R^2 = 0.9894; Stress = 0.1031). Weaknesses encompass insufficient government backing, poor access to information and public services, as well as low transparency, all of which diminish trust and obstruct collaboration. While monitoring and evaluation (2.67%) and management performance (2.87%) offer some leverage, they remain insufficient without stronger institutional backing (Fig. 9). Institutional transparency and accountability are critical for financial sustainability, credibility, and achieving SDGs (Cuadrado-Ballesteros and Bisogno, 2022). Strengthening governance frameworks, improving regulatory mechanisms, and enhancing transparency are therefore essential for building resilience and advancing long-term sustainability in Cianjur's agribusiness sector (Arif *et al*., 2021). This observation highlights that the environmental components of the agribusiness sub-terminal are less robust in comparison to the other aspects and necessitate increased scrutiny. While the environmental dimension already includes indicators such as resource efficiency, energy use, and waste management, a deeper ecological perspective is necessary. In particular, three issues are critical: i) emissions, mainly from diesel-based logistics and energy-intensive storage, which highlight the need for cleaner energy adoption; ii) land use pressures, where intensification and water demand can threaten soil and watershed stability, thus requiring conservation-oriented management; and iii) biodiversity risks, since monocropping and reduced habitat diversity may undermine ecosystem services. Although direct measures were not undertaken, these aspects frame important leverage points for future improvements. By associating the study outcomes with emission reduction, sustainable land use practices, and biodiversity preservation, the ecological facet of agribusiness infrastructure can be more effectively synchronized with long-term

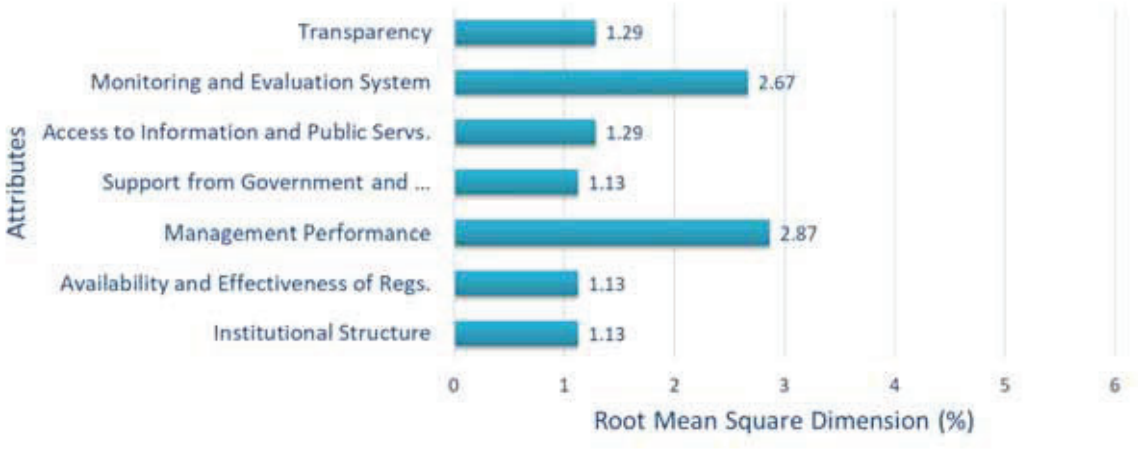

Fig. 9: Leverages of attributes for institutional dimension

objectives for environmental sustainability.

Given that the economic and technological dimensions showed the weakest performance in the MDS results, it is essential to highlight targeted interventions that could directly improve these domains. Economically speaking, interventions that improve access to financing (such as fintech lending and cooperatives), invest in value-added processing, and establish price stabilization mechanisms are essential. Technologically, upgrading cold storage, logistics, and traceability systems, combined with digital capacity building for farmers and managers, are required. Policy-driven incentives for renewable energy and smart technologies would significantly boost their adoption. Collectively, these measures could substantially strengthen the sub-terminal's sustainability profile.

SWOT analysis based on MDS results

The MDS analysis highlights key sustainability challenges for agribusiness sub-terminals across economic, social, environmental, technological, and institutional dimensions. Weaknesses include limited financing, price volatility, weak stakeholder engagement, poor environmental practices, and underdeveloped technology, which become major threats in the SWOT framework (Jahan *et al.*, 2022). Simultaneously, prospects like the adoption of fintech, enhanced waste management, and technological advancements provide avenues for resilience (Zhang and Wang, 2023). As summarized in Table 6, the SWOT matrix informed by MDS provides a comprehensive tool to balance these challenges and opportunities. It pinpoints essential areas for intervention and directs focused policies to enhance agribusiness sub-terminals and foster sustainable growth (Brenya *et al.*, 2022).

AST Cigombong's sustainability is shaped by both opportunities and threats. Technological innovations in cold storage and smart logistics improve efficiency (Khan *et al.*, 2025), while fintech expands capital and market access for smallholders. The implementation of green regulations, along with stakeholder collaboration, creates opportunities (Milovanova *et al.*, 2024). Conversely, climate change, land degradation, and regulatory uncertainty threaten productivity. From an internal perspective, the advantages consist of a strategic location and robust infrastructure; however, challenges persist in areas such as economic performance, governance, technology, and stakeholder representation. Addressing these gaps through better governance and inclusive practices is critical (Suryadharma *et al.*, 2024). The SWOT analysis outlines SO, WO, ST, and WT strategies, providing a roadmap for policymakers to enhance sustainability and resilience in Cigombong's agribusiness ecosystem (Kumar *et al.*, 2024).

Mapping MDS-SWOT-based strategic into thematic strategies

AST Cigombong's strategic direction focuses on leveraging existing strengths and mitigating key weaknesses through three thematic priorities identified from the MDS–SWOT analysis: financial

Table 6: Summarized SWOT matrix based on the discussions for each dimension

Sources	Strengths	Weaknesses
Internal factors	• Existing Infrastructure and Resources • Strategic Location and Access to Markets • Commitment to Environmental Sustainability	• Low Economic Sustainability Index • Weak Institutional Governance • Limited Technological Capacity • Underrepresentation of Stakeholders
	Opportunities	Threats
External factors	• Technological Advancements • Access to Capital and Market Expansion • Environmental Regulations and Green Supply Chain Practices • Collaboration and Stakeholder Engagement	• Climate Change and Environmental Risks • Regulatory Uncertainty and Market Volatility • Exclusion of Smallholder Farmers

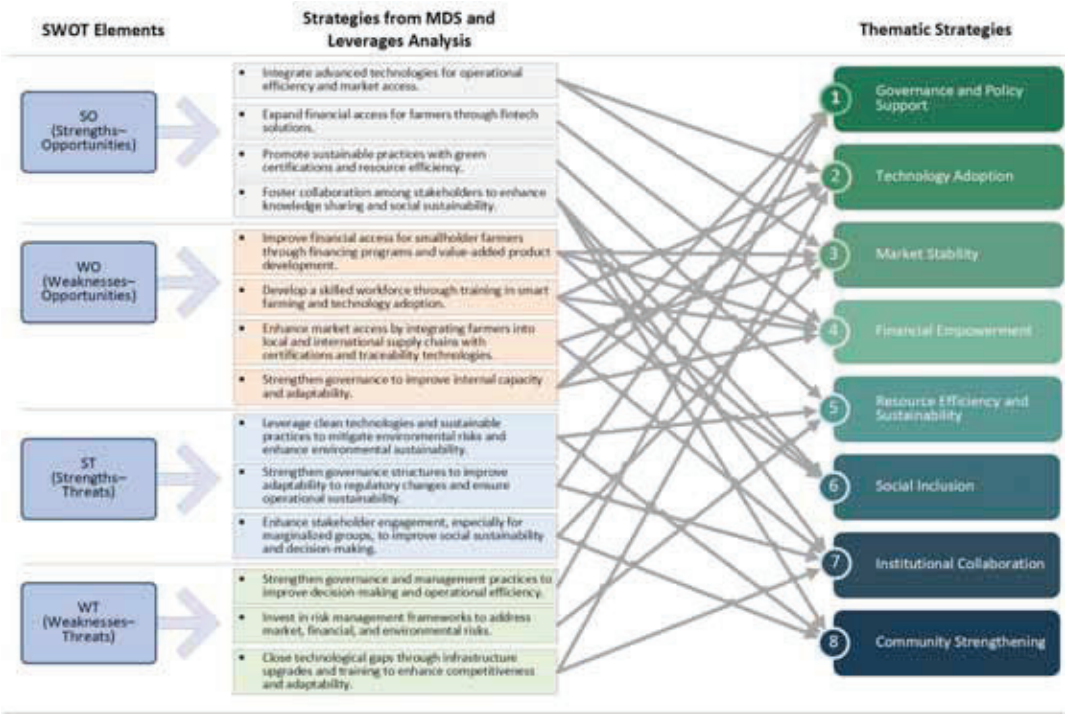

Fig. 10: Mapping MDS-SWOT-based strategic into thematic strategies for sustainable agribusiness sub-terminal

empowerment, technology adoption, and governance with multi-stakeholder policy support (Fig. 10). Focusing on these aspects emphasizes the most urgent sustainability issues while maintaining systemic integration, thus offering a viable route for enhancing agribusiness growth in Indonesia and beyond. SO, strategies emphasize advanced technology adoption, fintech-based financial access, sustainable practices, and stronger stakeholder collaboration, aligning with themes of Technology Adoption, Financial Empowerment, and Institutional Collaboration. WO strategies target improved

financial access for farmers, workforce skills development, enhanced market certification, and stronger governance (Akbar *et al*., 2023). Collectively, these strategies enhance operational efficiency, market access, and long-term sustainability. AST Cigombong's strategies are integrated into thematic areas of financial empowerment, market stability, technology adoption, and governance and policy support. ST strategies mitigate environmental risks through clean technologies, strengthen governance to adapt to changing regulations, and enhance social sustainability by including marginalized groups (Ikuemonisan, 2024). WT strategies focus on closing technological gaps, strengthening management, and investing in risk management, aligning with Governance, Technology, and Resource Efficiency themes. This strategic framework underscores the significance of building capacity, ensuring inclusivity, and strengthening resilience. Financial empowerment through fintech and financing programs reduces income volatility, while supply chain integration enhances market stability and reduces disparities. Social inclusion, emphasizing gender equality and marginalized groups, supports long-term sustainability (Mahwish *et al*., 2024). Enhancing resource efficiency through climate-smart agriculture bolsters ecological resilience, while digital innovations like automation and IoT boost productivity (Jiawei and Xinting, 2025). Robust governance ensures accountability and collaboration among stakeholders (Arun *et al*., 2023). Overall, AST Cigombong's strategic vision integrates technological innovation, financial empowerment, inclusivity, and governance to enhance efficiency, build resilience, and ensure sustainable growth.

Challenges and future directions

Despite its strategic potential, AST Cigombong remains constrained by systemic limitations that cut across economic, technological, social, environmental, and institutional domains. The MDS results highlight that economic and technological weaknesses remain the most critical sustainability gaps. These underscore enduring challenges of restricted financing, minimal value addition, and insufficient technology uptake, obstacles that impede smallholder competitiveness and hinder modernization. These weaknesses are compounded by institutional fragility, including fragmented policy support, limited transparency, and insufficient monitoring and evaluation mechanisms. The progress of social inclusivity is still insufficient, especially concerning gender equality, fair labor practices, and stakeholder engagement, which are fundamental to enhancing collective resilience. From an environmental perspective, the shortcomings in waste management, emission control, and water resource efficiency demonstrate the lack of circular economy practices and climate adaptation strategies. Future initiatives should aim to systematically blend all five aspects of sustainability. Within this framework, three priorities emerge as most critical: i) strengthening financial ecosystems through microfinance, cooperative lending, and digital fintech solutions; ii) accelerating technology adoption by improving infrastructure, digital platforms, and capacity building; and iii) reinforcing governance through participatory mechanisms, transparency, and coherent regulatory support within sub-terminal operations, in line with global low-carbon agendas. The establishment of participatory governance structures through institutional reforms continues to be vital. These targeted actions directly address the weakest dimensions while laying a solid foundation for long-term agribusiness resilience. Although the Cigombong AST is designed for Indonesia's distinct agro-ecological setting, the methodological approach and strategic takeaways are applicable to other humid tropical areas encountering comparable sustainability issues. The integrated MDS–SWOT framework provides a replicable tool that combines diagnostic assessment with strategic design, allowing policymakers in diverse contexts to identify leverage attributes and adapt interventions to local priorities (Amamou *et al*., 2025). Key strategic domains such as financial empowerment, technology adoption, and institutional collaboration are globally relevant. As an example, fintech-driven farmer credit and clean technologies, including solar-powered cold storage, can be customized for regions like West Africa or the Caribbean, where smallholders face similar limitations (Dharmayanti *et al*., 2023). Furthermore, the governance lessons from Cigombong, which highlight the risks of underutilization and weak institutional support, are highly applicable to regions where fragmented governance hinders agribusiness potential (Borelli *et al*., 2024The recommended sustainability assessment framework is flexible; it can be adjusted to respond to dynamic factors such as

altering climate, advancing markets, or technological upheaval. This adaptability can be achieved by regularly updating indicators with time-series data, integrating scenario analysis to explore alternative futures, and revising dimension attributes through expert and stakeholder inputs. To improve predictive accuracy beyond the present cross-sectional baseline, future work will implement longitudinal monitoring of the same attributes at regular intervals. This panel design facilitates out-of-sample validation, trajectory mapping within MDS space, and ongoing uncertainty evaluation for early-warning signals. Furthermore, leverage analysis and Monte Carlo simulations may serve as early-warning tools to detect attributes most sensitive to uncertainty. Together, these features allow the framework to remain robust and relevant in dynamic agribusiness environments.

CONCLUSION

This study applied the MDS framework to assess the sustainability of the AST Cigombong across five key dimensions: economic, social, environmental, technological, and institutional. The results indicate that AST Cigombong is less sustainable, particularly in terms of economic and technological factors, emphasizing the pressing requirement for financial reforms and digital transformation. Government and institutional support remain fragmented and insufficient, failing to provide the necessary regulatory, informational, and service-based foundations for sustainable agribusiness growth. These findings underscore the urgent need for systemic reforms to improve financing mechanisms, strengthen institutional capacity, accelerate the adoption of digital and climate-smart technologies, and promote social inclusivity in agribusiness development. The strategic framework created in this research underscores three main essential areas: financial empowerment, technology adoption, and governance with policy support. Focusing on these dimensions provides a practical and policy-relevant roadmap for transforming agribusiness sub-terminals into resilient and sustainable hubs, while maintaining methodological rigor and ensuring feasibility in implementation. Nonetheless, the study presents some constraints, including its emphasis on one specific sub-terminal, potentially hindering the broader relevance of the conclusions, and its reliance on expert assessments, which adds a layer of subjectivity despite the presence of statistical validation. Additionally, cross-sectional design only captures present conditions, without accounting for dynamic shifts in markets, institutions, or environmental pressures. Subsequent research should therefore implement longitudinal and comparative methodologies across different areas, incorporating mixed methods and big data analytics to effectively capture the dynamic trajectories of sustainability. Despite these limitations, the AST Cigombong case provides valuable empirical insights and strategic lessons that can inform broader efforts to strengthen agribusiness infrastructure, improve rural livelihoods, and promote sustainable agriculture in Indonesia.

AUTHOR CONTRIBUTIONS

S.J. Munarso developed the initial study plan, analyzed the manuscript's scientific content, and provided overall guidance. A. Hendriadi contributed to the study plan, analyzed the content, and helped draft the conclusion. H.M. Elmatsani led conceptualization, literature review, supervised data collection, and revised the manuscript. A. Arianto facilitated institutional collaboration, co-drafted the manuscript, evaluated coherence, and contributed to revisions. B. Benyamin collected field data, implemented the survey, helped draft the manuscript, and assisted with data analysis. N. Sjafrina participated in data collection, co-authored the manuscript, and contributed to the results and discussion. S.I. Kailaku was responsible for data gathering, analysis, and manuscript revisions. M.J. Djafar refined the manuscript formatting, co-authored the manuscript, and contributed to revisions. P. Astuti managed the project, supervised data collection, analyzed data, and helped draft the manuscript. A. Latif critically reviewed the manuscript, contributed to interpreting findings, and suggested improvements. W. Purwanta provided a critical review and recommended revisions as corresponding author. H. Daulay refined the manuscript's technical aspects, and A.D. Santoso focused on the scientific validity of the analysis. All authors reviewed and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
AI	Artificial intelligence
AST	Agribusiness sub-terminal
AHP	Analytical Hierarchy Process
ALSCAL	Alternating Least Squares Scaling (an algorithm of MDS)
BRIN	Badan Riset dan Inovasi Nasional
d	Euclidean distance
dij	Euclidean distance from point i to point j
dijk	Squared distance
EPR	Extended producer responsibility
Eq	Equation
FAO	Food and Agriculture Organization
FGD	Focus group discussions
GCG	Good corporate governance
ha	Hectare
ILO	International Labor Organization
IoT	Internet of things
i, j, k	Dimensions
MDS	Multidimensional scaling
NGOs	Non-Government Organizations
Oij	Point of origin
RAPFISH	Rapid appraisal for fisheries
R^2	Coefficient of determination
Stress	Dissimilarities in MDS
RMS	Root mean square
S	Stress
SQR	Structured query reporter
SAFA	Sustainability Assessment of Food and Agriculture
SMEs	Small medium enterprises
SNI	Indonesian national standard
SOP	Standard operating procedure
SDGs	Sustainable development goals
y	Year

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REVIEW PAPER

Emerging frontiers in ecosystem and biodiversity monitoring using remote sensing and geographic information systems

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ABSTRACT

The accelerating biodiversity crisis, driven by climate change and intensifying anthropogenic pressures, demands accurate, scalable, and dynamic tools to monitor ecosystem health and biological diversity. Remote sensing and geographic information systems have long been pivotal in observing environmental conditions and measuring biodiversity, nonetheless, the fast-paced development of sensing technologies, analytical approaches, and computational power is greatly transforming their purpose in conservation science. This study provides a comprehensive synthesis of next-generation applications of remote sensing and geographic information systems in biodiversity and ecosystem monitoring. The study aimed to gather recent developments in the use of remote sensing and geographic information systems for biodiversity and ecosystem monitoring, thoroughly evaluate existing methods, recognize enduring challenges, and recommend innovative, technology-driven pathways for improving ecological assessments and conservation planning. A notable transition is taking place from standard land cover mapping towards assessing ecological functions, evaluating habitat quality, and detecting environmental changes in near real-time. Innovative technologies, including hyperspectral imaging, drone-based sensing, radar interferometry, three-dimensional laser scanning, and small satellite constellations, are combined with sophisticated computational methods, featuring machine learning, deep learning, spatiotemporal data fusion, and cloud-based geo-processing. These developments are transforming applications ranging from automated species distribution modelling and ecosystem service mapping to structural-functional landscape phenotyping, habitat connectivity assessment, and predictive early-warning systems for biodiversity loss. The merging of datasets with differing resolutions, timeframes, and sensors is promoting the establishment of broad ecological intelligence, which contributes to adaptive conservation strategies and evidence-based environmental governance. Despite these advances, several challenges remain, including algorithmic bias, the harmonization of heterogeneous datasets, limited direct biodiversity proxies, and disparities in access to emerging technologies. Ethical considerations along with the integration of community-driven monitoring frameworks, are essential for ensuring that technological advancements are in harmony with global sustainability goals. Anticipating the future, the integration of sophisticated sensing technologies, artificial intelligence, and cloud computing platforms presents remarkable opportunities to transform biodiversity monitoring and conservation planning. By enabling predictive, adaptive, and near real-time decision-making, these innovations are reshaping strategies for environmental management and the development of resilient socio-ecological systems in the context of rapid global change.

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INTRODUCTION

Climate change and anthropogenic activities are driving unprecedented alterations in global biodiversity and ecosystem functioning. It is anticipated that by the end of the century, the world will see a temperature increase of 3 to 4 degrees Celsius (°C), leading to changes in species' morphology, behavior, and geographic distribution, which will disrupt ecosystem services essential for human welfare (Shivanna, 2022). These ecological changes are further compounded by land-use transformations, where cropland expansion has increased by over 26 percent (%) in protected areas such as Burkina Faso's Bontioli Nature Reserve, coinciding with significant losses in natural vegetation (Kiribou *et al.*, 2024). A significant relationship exists between the rapid growth of the human population and changes in land cover, which increases the stress on natural ecosystems and complicates efforts to conserve biodiversity. Despite nearly 2,000 scientific articles published between 2000 and 2021 on climate and biodiversity conservation, significant geographic and interdisciplinary knowledge gaps remain, particularly in underrepresented regions and complex socio-ecological systems (Farooqi *et al.*, 2022; Depari, 2024). This deficiency in integration has hindered the ability of natural resource managers to create adaptive, data-centric strategies that are responsive to the fluctuations in biodiversity. There is an urgent need for comprehensive frameworks that bridge ecological, technological, and policy perspectives to enable scalable and predictive biodiversity monitoring. Conventional approaches to biodiversity assessment, including field surveys, camera trapping, and ecological sampling, are fundamental yet face certain limitations. Field surveys relying on visual and aural observations are labor-intensive, time-consuming, and constrained to limited spatial and temporal scales, reducing their effectiveness for capturing complex biodiversity patterns (Bell and Malerba, 2025). Additionally, while camera trapping effectively documents species presence, it is hindered by the high costs associated with deployment, ongoing maintenance requirements, and a bias towards detecting more prominent species, often missing out on elusive or less active taxa (Oliver *et al.*, 2023). Furthermore, their restricted temporal coverage can miss rare events and seasonal behavioral shifts. Similarly, traditional ecological sampling requires expert knowledge, involves significant logistical challenges in remote or rugged terrains, and incurs prohibitive costs when repeated surveys are needed for long-term monitoring (Fergus *et al.*, 2024). These restrictions diminish scalability and may cause biodiversity assessments to be incomplete or biased, thereby hindering effective ecosystem management. Recent technological advancements in remote sensing (RS) and geographic information systems (GIS) offer promising solutions to these challenges. RS platforms, including satellite imagery and drone-based systems, now provide unprecedented capabilities to capture real-time ecosystem dynamics across spatial and temporal scales, supported by diverse spectral, spatial, and temporal resolutions (Lausch *et al.*, 2020; Martínez-López *et al.*, 2021; Marvasti-Zadeh *et al.*, 2024). Integrating these innovations with community-driven monitoring frameworks presents a transformative opportunity to develop scalable, adaptive, and data-rich approaches for biodiversity conservation and sustainable land-use planning in the Anthropocene (Weiskopf *et al.*, 2020). These distinct abilities facilitate thorough and scalable observation of ecosystems across multiple levels. RS has the ability to capture both the structural and functional aspects of ecosystems, delivering vital insights into environmental conditions. The integration of vegetation indices significantly enhances the detection of ecological changes relevant to biodiversity (Yan *et al.*, 2025; Ekaputri *et al.*, 2024; Basyuni *et al.*, 2024). Commonly used indices such as normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), and soil adjusted vegetation index (SAVI) quantify vegetation health and coverage (Melnyk and Brunn, 2025). Furthermore, structural proxies based on light detection and ranging (LiDAR) offer three-dimensional data concerning vegetation and landscape characteristics (Keerthinathan *et al.*, 2025). Tracking these changes over time supports understanding of ecosystem responses to natural and anthropogenic pressures. Remote sensing thus enables broad, continuous, and non-invasive monitoring at scales difficult to achieve with traditional methods (Lawley *et al.*, 2016). This feature is fundamental for well-informed conservation and resource management initiatives. As a result, RS platforms are increasingly valuable for advancing ecological research. The integration of diverse data

types enables a complete perspective on the ecosystem vitality and biodiversity dynamics. Moreover, technological advances in artificial intelligence (AI) and machine learning have revolutionized ecological data analysis (Chen *et al.*, 2024; Pichler and Hartig, 2023; Ryo, 2024). These innovations enable automated processing of vast amounts of environmental data with high accuracy. Cloud-based geospatial platforms, like Google Earth Engine, provide scalable infrastructure for managing and analyzing large spatial datasets (Gorelick *et al.*, 2017). Collectively, these technologies enable species distribution modeling, which forecasts the probable locations of species based on environmental factors. They also enable the detection of disturbances, such as deforestation or habitat degradation, by analyzing changes over time. Phenological tracking, or monitoring seasonal biological events, is made more efficient and precise through these tools (Park and Post, 2022). This quick processing facilitates the prompt identification of ecological changes that could otherwise be overlooked. Consequently, conservation planners can make informed decisions more quickly to protect vulnerable species and ecosystems. Automation reduces manual labor and speeds up data interpretation, increasing overall efficiency. The integration of AI and cloud platforms is transforming biodiversity monitoring into a more dynamic and responsive practice (Bibri *et al.*, 2024). These skills are vital for adjusting conservation initiatives as environmental changes accelerate. Ultimately, these technological advances support more effective and proactive biodiversity management worldwide. In spite of these advancements, there is still limited information on how to successfully merge multi-source RS data, functional trait detection, and socio-ecological indicators into unified biodiversity monitoring frameworks, particularly for complex ecosystems and areas in the global south that are deficient in data. This review study uniquely integrates advances in remote sensing, GIS, and AI-driven analytical frameworks with participatory and cross-disciplinary approaches, providing actionable pathways for predictive, high-resolution, and socially inclusive biodiversity monitoring that extend beyond summarizing existing methods. This study provides an extensive and future-oriented examination of emerging RS and GIS technologies, analytical approaches, and applied frameworks for monitoring biodiversity and ecosystem changes. It emphasizes the need to overcome current challenges and to define future research paths that support adaptive, inclusive, and intelligent ecological decision-making systems. This study aims to consolidate recent advancements in RS and GIS applications for the monitoring of biodiversity and ecosystems, critically evaluate existing methodologies, identify persisting challenges, and propose innovative, technology-driven strategies for enhancing ecological assessments and conservation planning. This study has been carried out globally, integrating research findings from diverse ecosystems and regions, and was conducted in the year 2025 to reflect the most recent developments and emerging trends in the field.

METHODOLOGY

Search strategy and sources

A systematic literature search was conducted using four primary academic databases: Scopus, Web of Science, and ScienceDirect. The selection of these databases is based on their broad coverage of environmental sciences, geospatial technologies, and studies related to biodiversity monitoring. To complement these, Google Scholar was used to capture additional grey literature, including technical reports, case studies, and regionally focused investigations not indexed in the primary databases. The strategy for searching included the integration of various keywords along with Boolean operators to enhance the retrieval of pertinent studies. Search terms included combinations such as “remote sensing,” “satellite imagery,” “hyperspectral imaging,” “drone-based sensing,” “biodiversity monitoring,” “ecosystem health,” “species distribution modeling,” “GIS,” “spatial analysis,” “functional ecological assessment,” “real-time change detection,” and “landscape phenotyping.” To include the most recent technological breakthroughs, the search focused on studies released between 2015 and 2025, a span during which there were significant advancements in hyperspectral imaging, drone-based platforms, radar interferometry, Cube Satellite (CubeSat) constellations, and advanced analytical techniques, including machine learning, cloud computing, and spatiotemporal data fusion.

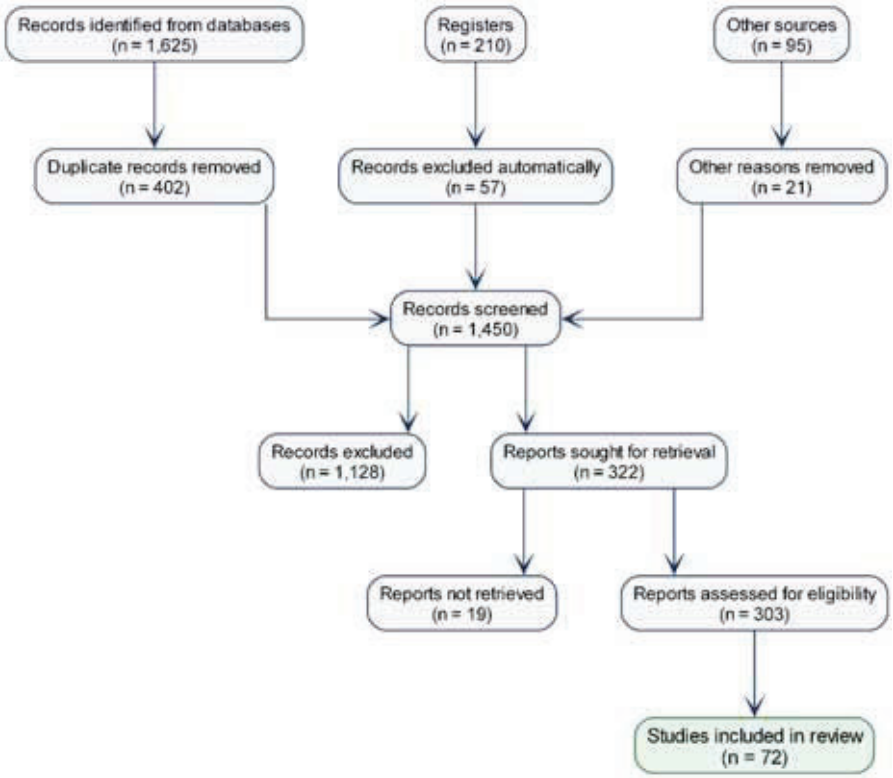

Fig. 1: PRISMA 2020 flow diagram showing the identification, screening, eligibility assessment, and inclusion of studies in the systematic review

Inclusion and exclusion criteria

Studies were accepted if they employed advanced RS or GIS technologies for the purposes of biodiversity monitoring, ecosystem evaluation, or species distribution modeling. Priority was given to studies that demonstrated integration of multi-resolution, multi-sensor, or multi-temporal datasets and those that employed emerging analytical frameworks such as machine learning, deep learning, or cloud-based geospatial analytics. Studies based on empirical evidence, whether they yield quantitative or qualitative outcomes, and systematic reviews that summarize technological innovations, were also viewed as relevant. Studies were excluded if they focused exclusively on traditional land cover mapping without linking results to biodiversity or ecological parameters, lacked methodological clarity, or failed to provide sufficient detail on data sources and analytical approaches. Publications presenting purely theoretical frameworks without empirical validation were also excluded. Moreover, only studies that were published in English were included to guarantee consistency in interpretation, considering the subject's technical complexity. The study selection process for the systematic review is summarized in the PRISMA flow diagram (Fig. 1), illustrating the numbers of records identified, screened, assessed for eligibility, and ultimately included.

Study selection, scope, and data synthesis

All search results were transferred to Zotero for organization and systematic screening, with duplicates cleared and the remaining studies initially reviewed by title and abstract for relevance. Full-text articles were then evaluated against predefined inclusion criteria, prioritizing studies employing advanced technologies such as hyperspectral imaging, drone-based sensing, radar interferometry, and CubeSat constellations, particularly those demonstrating novel applications in biodiversity monitoring, species distribution modeling, structural-functional landscape phenotyping, or

real-time ecological change detection. The review covered a variety of ecosystems and geographical areas, such as biodiversity hotspots, protected regions, urban settings, and marine environments, focusing on research from low- and middle-income countries where limited data and infrastructure issues hinder extensive monitoring. For each study, detailed information was extracted on the type of RS or GIS technology, dataset resolutions, analytical frameworks, biodiversity metrics, sampling protocols, objectives, key findings, limitations, and potential policy implications. Due to the methodological diversity, a qualitative synthesis was performed to uncover shared themes, emerging technological trends, analytical progress, and ongoing knowledge deficiencies.

Technological convergence in ecosystem and biodiversity monitoring

Hyperspectral and multispectral satellite imaging

Recent progress in hyperspectral and multispectral satellite imaging has notably broadened the scope of remote sensing in ecological monitoring, shifting from standard broadband indices to the classification of species and biochemical characteristics. For instance, the use of spaceborne sensors such as precursore iperspettrale della missione applicativa (PRISMA), DLR earth sensing imaging spectrometer (DESIS), and environmental mapping and analysis program (EnMAP) has demonstrated exceptional potential for identifying vegetation characteristics, detecting plant physiological traits, and delineating individual species. Lassalle *et al.* (2023) illustrated this by achieving classification accuracies of up to 97% (OA) and 0.95 (Kappa) in mangrove species mapping using multisource data, including DESIS and PRISMA. Their findings also highlight the superior performance of hyperspectral imagery at sub-metric resolutions with 0.5 meters (m), especially when incorporating short-wave infrared (SWIR) bands. Furthermore, Lu *et al*. (2020) pointed out the importance of hyperspectral imaging in agriculture for identifying minor spectral variations related to crop biochemical and morphological features, facilitated by the rise of compact, cost-effective airborne sensors and improved access to satellite data. The EnMAP mission further reinforces this technological leap, offering 30 m spatial resolution and high spectral sampling with 6.5–10 nanometers (nm) across the VNIR and SWIR regions (Chabrillat *et al.*, 2024). Since its operational launch in 2022, EnMAP has provided high signal-to-noise, globally accessible data that support diverse environmental applications, including vegetation analysis, soil composition mapping, and water quality monitoring. Fig. 2 classifies the new remote sensing and GIS technologies, analytical methods, applications, and challenges, underlining their interconnected roles in the observation of biodiversity and ecosystems.

Radar and LiDAR for structural complexity

Forest structural complexity serves as a vital determinant of both biodiversity and ecosystem performance, however, effectively measuring this complexity on a large scale continues to be a challenge. Synthetic aperture radar (SAR) and light detection and ranging (LiDAR) technologies have emerged as powerful tools to characterize forest structure, above-ground biomass, and habitat heterogeneity. In particular, LiDAR supplies exact three-dimensional information that supports the estimation of vital forest features such as canopy height, biomass, and volume, which are deeply connected to habitat quality. Coops *et al.* (2021), demonstrate that LiDAR-derived models can explain a substantial portion of the variability in forest height (mean R^2 = 0.64) and biomass (mean R^2 = 0.55) across diverse forest landscapes, highlighting the technology's capacity to generate spatially explicit, accurate structural metrics. Achieving this level of precision is vital for grasping the complexity of habitats in both managed and natural woodlands. The combination of LiDAR and optical remote sensing significantly improves the capacity to observe structural dynamics across extended time periods. Tanase *et al.* (2024), effectively combined airborne and space borne LiDAR with Landsat time series to reveal significant increases in forest canopy cover and biomass over nearly four decades in the Iberian Peninsula. Their findings, including an 11% increase in canopy cover and biomass rising from approximately 32 to 50 tons per hectare (t/ha), underscore the power of combining spectral and structural data to track forest recovery and growth trends relevant for biodiversity assessments and carbon accounting. Bae *et al.* (2019), illustrate that habitat structure metrics obtained from radar are comparable to those from airborne LiDAR in forecasting biodiversity patterns across various taxa.

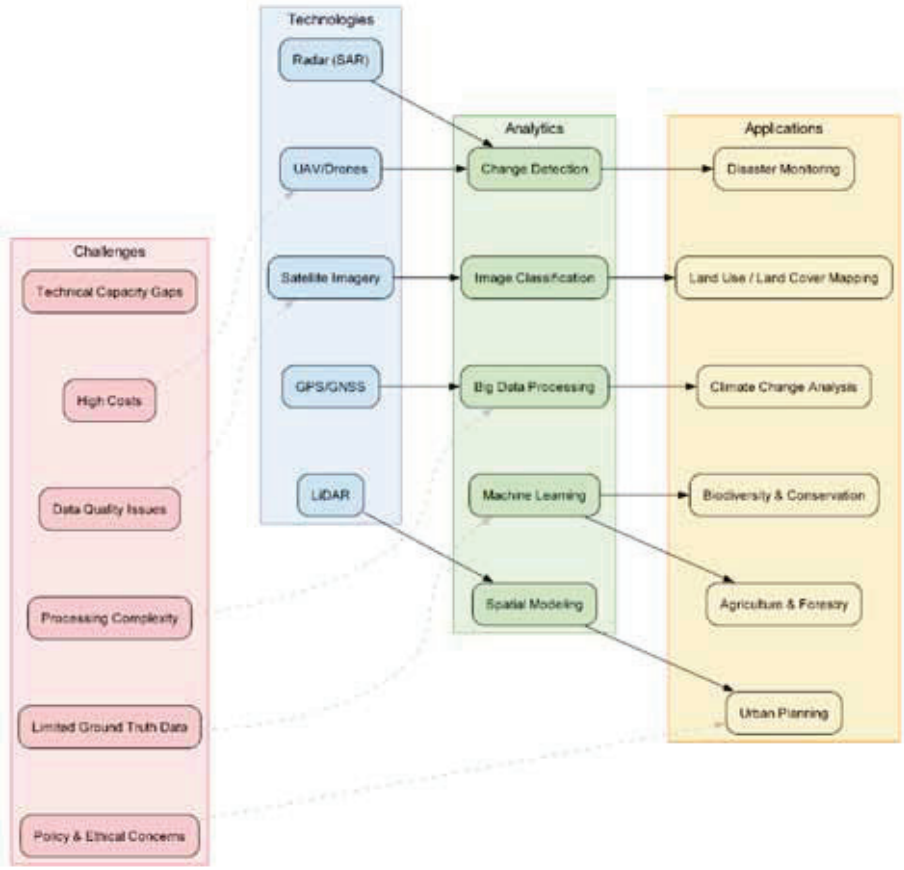

Fig. 2: Key remote sensing and GIS technologies, analytics, applications, and challenges

Their results indicate that SAR achieves comparable, and in some cases superior, predictive power (median R^2 = 0.57 vs. 0.51 for LiDAR) for species assemblage composition, emphasizing radar's suitability for large-scale biodiversity monitoring where cloud cover or logistical constraints limit LiDAR acquisition. Radar's capability to penetrate canopies and react to the moisture and structure of vegetation offers distinct, supplementary insights that improve ecosystem characterization. Advances in multi-sensor fusion further leverage the strengths of these technologies. Lutz *et al.* (2024), show that integrating global ecosystem dynamics investigation (GEDI) LiDAR canopy height data with sentinel-1 synthetic aperture radar (SAR) and multispectral imagery can robustly estimate aboveground biomass density across varied vegetation types in Western Australia, ranging from tall eucalypt forests to savanna grasslands.

UAVs and CubeSat constellations

The introduction of cost-effective unmanned aerial vehicles (UAVs) and high-frequency CubeSat constellations including PlanetScope has changed the landscape of environmental monitoring on both local and regional scales, offering exceptional spatial and temporal resolution. These technologies enable rapid, cost-effective surveillance that is critical for detecting subtle and transient ecological phenomena, disturbances, and illegal activities, which are often missed by traditional satellite systems with coarser revisit times or spatial footprints. UAVs that are equipped with multispectral sensors enable highly detailed observations at the required scales for precision agriculture and habitat monitoring. In contrast, CubeSat constellations deliver daily global coverage with moderate spatial resolution, which supports near real-time evaluation of phenological

and land cover dynamics. Moletto-Lobos *et al.* (2024), highlight the complementary capabilities of UAV multispectral data and PlanetScope satellite imagery in monitoring winter wheat phenology and fertilization practices in Mediterranean agroecosystems. Their findings demonstrate that PlanetScope's moderate resolution (approximately 3-5 m) is sufficient for capturing canopy cover variations (R^2 = 0.68) and crop yield estimates (R^2 = 0.54) across heterogeneous fields, although it tends to smooth over fine-scale treatment variability that UAVs can better resolve. This complementarity underscores the potential for integrated UAV and CubeSat data streams to optimize agricultural management and enhance climate-resilient practices through continuous monitoring of crop status and productivity. Furthermore, CubeSat constellations have shown to be valuable for monitoring biodiversity-related phenology beyond agricultural uses. Miura *et al.* (2023), effectively utilized PlanetScope's imagery, which offers high temporal and spatial resolution, to identify general flowering events in the dipterocarp forests of Borneo. They were able to capture both the timing and spatial extent of synchronous mass flowering, revealing moderate to strong correlations (0.52–0.85) to in situ phenology observations. In semi-arid environments, where phenological patterns are spatially heterogeneous and temporally irregular, Liu *et al.* (2024), validate PlanetScope's ability to detect plant-specific phenology metrics, such as green up and senescence timings, with good agreement to ground-based PhenoCam observations (average R^2 up to 0.84 during green up phases). Even with ongoing delays in recognizing the onset of senescence and dormancy, PlanetScope's dependable performance and precise temporal resolution allow for intricate monitoring of vegetation dynamics in challenging ecosystems, which is essential for adaptive approaches in land and water management. Fig. 3 presents an integrated RS–GIS framework for biodiversity monitoring and conservation.

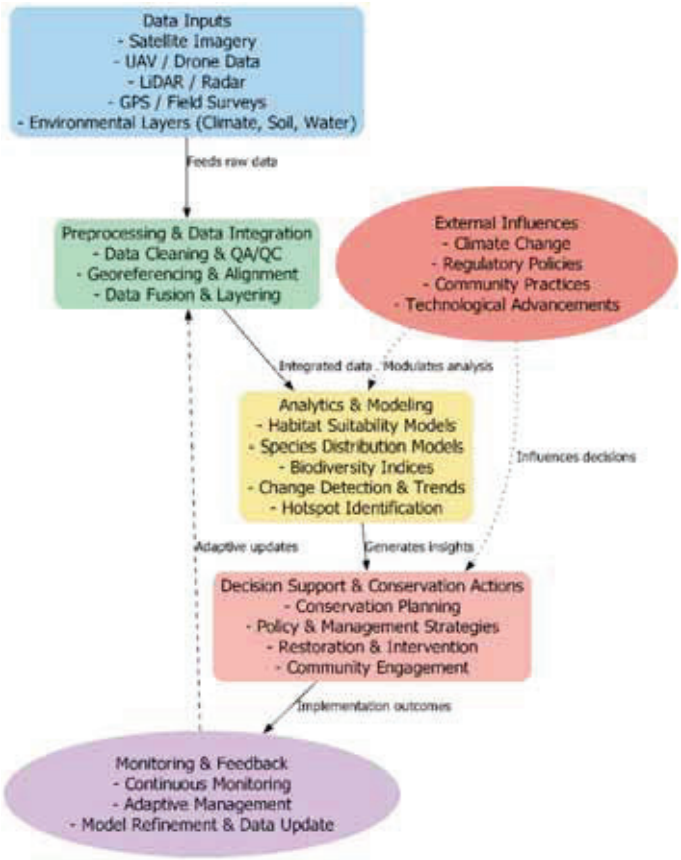

Fig. 3: Integrated RS–GIS framework for biodiversity monitoring and conservation

Moving beyond NDVI

Despite its importance, the NDVI has limitations in assessing complex physiological states such as canopy water content, stress responses, and photosynthetic efficiency, even though it is a key tool in vegetation monitoring due to its simplicity and robustness. Consequently, more refined vegetation indices like the EVI, photochemical reflectance index (PRI), normalized difference water index (NDWI), and red-edge based metrics have been increasingly adopted to provide nuanced insights into canopy stress, water status, and productivity beyond what NDVI can reliably detect. Zhang and Zhou (2019), indicated that indices focused on vegetation water content, especially those employing red-edge spectral bands such as the green chlorophyll index (CIgreen), red edge normalized ratio (NRred edge), and red-edge chlorophyll Index (CIred edge), exhibited greater sensitivity to fluctuations in canopy water content (CWC) under water stress conditions in summer maize. It was found that CWC presented a significant single-peak seasonal fluctuation and was the most reliable predictor of crop water status among the investigated parameters. Their study emphasized the optimal predictive power of these indices over others like leaf equivalent water thickness (EWT) and live fuel moisture content (LFMC). In a related study, Zhu *et al*. (2024) pointed out the effectiveness of indices that utilize near-infrared (NIR) and shortwave infrared (SWIR) bands, including the Normalized Difference Infrared Index (NDII), Moisture Stress Index (MSI), Photochemical Reflectance Index (PRI), Land Surface Water Index (LSWI), and Global Vegetation Moisture Index (GVMI) in the context of for drought monitoring in grasslands. Their coupled radiative transfer modeling and satellite band evaluation showed silhouette coefficients exceeding 0.7 for NDII, MSI, PRI, LSWI, and GVMI during the stable growth stage, indicating high sensitivity to drought conditions. Among satellites analyzed, MODIS Band 7 showed the highest sensitivity to water content, which further emphasizes the importance of these indices for drought detection over standard NDVI. Further supporting this, Zhou *et al.* (2022), conducted irrigation experiments on maize and demonstrated that while NDVI and other traditional indices exhibited some sensitivity to canopy water content, the Water Index (WI) and NDWI provided stronger linear relationships with CWC, with coefficients of determination (R^2) around 0.55 to 0.57 within a CWC range of 0.01-0.41 kilogram per square meter (kg/m²). Conversely, both NDVI and the Optimal Soil-Adjusted Vegetation Index (OSAVI) demonstrated similar but diminished predictive strength, with key threshold values identified at 0.55 kg/m² for vegetation water content. These indices also reflected dynamic water content changes better than NDVI throughout the growing season, underscoring their utility in agricultural drought assessment and irrigation management.

Machine learning and deep learning applications

Machine learning (ML) and deep learning (DL) play a crucial role in environmental and ecological studies, providing robust tools for classification, anomaly detection, and predictive modeling with impressive precision. Talaei Khoei and Kaabouch (2023), compared a suite of supervised and unsupervised models on the Canadian Institute for Cybersecurity Distributed Denial of Service 2019 Dataset (CICDDOS 2019) benchmark dataset for intrusion detection, demonstrating that the Alex Neural Network (a deep learning model) achieved the highest detection accuracy among supervised models, outperforming traditional algorithms such as Gaussian Naïve Bayes and Support Vector Machines (SVM). Regarding unsupervised learning, the Variational Autoencoder model exhibited outstanding performance, highlighting the enhanced capability of deep architectures in identifying intricate patterns without relying heavily on labeled data. This highlights the potential of DL for ecological anomaly detection where labeled datasets are often scarce. This study, although centered on cybersecurity, illustrates the ability of deep learning architectures for detecting complex patterns in high-dimensional datasets. By analogy, similar approaches could be applied to biodiversity monitoring, where ecological anomaly detection often faces scarce labeled data and complex, nonlinear relationships among environmental variables and species observations. Chowdhury *et al.* (2024) pointed out the significance of merging machine learning and artificial intelligence with geographic information systems and remote sensing in their examination of coral reef surveillance, particularly to track the health of coral reefs facing the pressures of climate change. The study identified Random Forests, Convolutional Neural

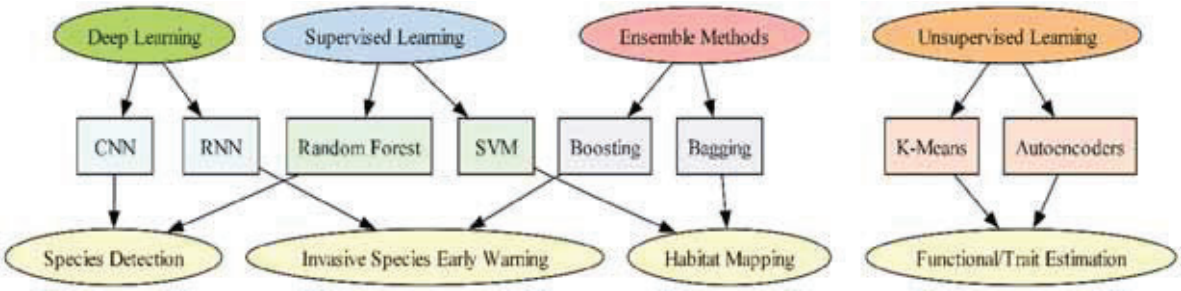

Fig. 4: Conceptual overview of innovative machine learning approaches in RS–GIS for biodiversity monitoring– Recurrent neural network (RNN)

Networks (CNNs), and transfer learning as dominant frameworks enabling high-accuracy classification of reef conditions, detection of bleaching events, and habitat degradation. Fig. 4 presents a conceptual framework of advanced machine learning strategies implemented in RS–GIS for biodiversity monitoring, demonstrating the links between categories of algorithms, specific methodologies, and their key ecological applications.

Table 1 provides an overview of innovative machine learning approaches integrated with RS–GIS technologies for enhancing biodiversity monitoring and assessment.

Spatiotemporal data fusion

Techniques for spatiotemporal data fusion, including STARFM and BFAST, have substantially increased the capability for ongoing landscape monitoring of landscapes and the early detection of environmental changes by skillfully combining coarse-resolution and fine-resolution remote sensing imagery. Wu *et al.* (2020), applied the breaks for additive seasonal and trend (BFAST) algorithm integrated with random forests to monthly Landsat NDVI time series over the West Dongting Lake wetland in China, achieving an overall accuracy of 87.8% in detecting multiple types of forest changes including deforestation, reforestation, and flooding-related variations between 2000 and 2018. The study's outcomes demonstrated clear spatiotemporal forest dynamics, featuring rapid plantation growth from 2000 to 2005, a stabilization phase from 2006 to 2011, and a decline mainly caused by human-induced factors. Building on the need for efficient and scalable change detection, Masiliūnas *et al.* (2021), introduced BFAST Lite, a lightweight unsupervised time series analysis method optimized for speed and flexibility. Tested against an 11-year MODIS dataset with over 30,000 global land cover change points, BFAST Lite matched the accuracy of the original BFAST but significantly outperformed it in processing speed and robustness to missing data. This algorithm reached a perfect balance between user and producer accuracy by using alternative alternative information criteria to identify change breaks, making it particularly effective for large-scale environmental monitoring. More recently, Li and Wu (2024), developed Multi-RLD-Net, a deep learning-based multi-task network for precise change area identification and exact change moment detection in multispectral time series imagery from platforms such as Landsat and Sentinel-2. By combining Optical Flow and Long Short-Term Memory (LSTM) networks, Multi-RLD-Net effectively aligns temporal features and captures long-term dependencies, resulting in a substantial performance gain. Their experiments conducted on benchmark datasets (UTRNet and DynamicEarthNet) revealed enhancements in in F1 scores of 1.29% and 10.42% compared to previous leading method MC2ABNet, respectively, emphasizing the strength of sophisticated spatiotemporal fusion integrated with deep learning for comprehensive environmental change analysis (Fig. 5).

Applications in biodiversity and ecosystem monitoring

Species distribution and habitat risk mapping

RS-GIS tools support dynamic modeling of species distributions under climate and land-use change scenarios, aiding conservation prioritization. These tools facilitate the incorporation of various environmental factors and spatial information to forecast possible changes in the suitable habitats

Table 1: Innovative machine learning approaches in RS–GIS for biodiversity

Methodology	Description	Data requirements	Typical algorithms / models	Advantages	Limitations	Applications in Biodiversity	Sources
Transfer Learning	Reusing models trained in data-rich regions or large datasets for data-poor biodiversity regions.	Labeled RS–GIS data from source domain; minimal local labeled data.	Pretrained CNNs (Residual Network, Visual Geometry Group Network), Vision Transformers.	Reduces local data needs; accelerates deployment.	Domain mismatch risk; requires adaptation.	Mapping species in under-surveyed regions; habitat classification.	Kaya *et al.*, 2019; Sun *et al.*, 2022; Tariku *et al.*, 2023
Explainable AI (XAI)	Methods that reveal why models make certain predictions.	Labeled imagery; model predictions and features.	SHapley Additive exPlanations, Local Interpretable Model-Agnostic Explanations, Gradient-weighted Class Activation Mapping, Integrated Gradients.	Builds trust; identifies biases; supports regulation.	May lower performance; explanations may be complex.	Policy-compliant habitat mapping; identifying bias in endangered species models.	Ali *et al.*, 2023; Haque *et al.*, 2023; Saeed and Omlin, 2023
Ensemble Learning	Combining multiple models to improve predictive accuracy.	Any labeled biodiversity RS–GIS dataset.	Random Forests, Gradient Boosting, Model Averaging, Stacking.	Reduces overfitting; more robust predictions.	Higher computation; less interpretable.	Forest type mapping; multi-species habitat prediction.	Ganaie *et al.*, 2022; Mienye and Sun, 2022; Mohammed and Kora, 2023
Unsupervised Learning for novelty detection	Detecting rare or unexpected patterns without prior labels.	Unlabeled RS–GIS or sensor data.	Density-Based Spatial Clustering of Applications with Noise, Isolation Forest, k-Means, Self-Organizing Maps.	Finds new species/events; early warnings.	Difficult validation; false positives.	Rare species detection; invasive species alerts.	Bergmann *et al.*, 2021; Eltouny *et al.*, 2023; Hossen *et al.*, 2024
Data augmentation and synthetic data generation	Expanding datasets via transformations or synthetic generation.	Limited labeled data.	Generative Adversarial Networks, StyleGAN, image rotation/scaling methods.	Overcomes scarcity; boosts robustness.	Synthetic data may lack realism.	Rare species detection in low-data regions.	ANNAKI *et al.*, 2024; Sung *et al.*, 2022
Few-shot learning	Learning from a few examples per class.	Few labeled examples, plus background data.	Matching Networks, Prototypical Networks.	Useful for rare/endangered species.	Sensitive to variability.	Identifying rare orchids from aerial imagery.	Song *et al.*, 2023; Tian *et al.*, 2024; Ye *et al.*, 2024
Semi-Supervised Learning	Leveraging small labeled + large unlabeled datasets.	Large unlabeled imagery, small labeled subset.	Semi-supervised CNNs, Mean Teacher, Pseudo-labeling.	Reduces annotation costs; boosts accuracy.	Unlabeled data quality critical.	Mapping understudied habitats.	van Engelen and Hoos, 2020; Verma *et al.*, 2022; Yang *et al.*, 2023
Self-Supervised Learning	Pretraining with proxy tasks, then fine-tuning.	Large unlabeled datasets.	Simple Framework for Contrastive Learning of Visual Representations, Momentum Contrast, Bootstrap Your Own Latent.	Avoids costly labeling; uses massive RS data.	Requires relevant pretext tasks.	Broad-scale vegetation mapping.	Jaiswal *et al.*, 2020; Liu *et al.*, 2021; Rani *et al.*, 2023
Active Learning	Selecting most informative samples for labeling.	Initial small labeled dataset + large unlabeled pool.	Uncertainty Sampling, Query-by-Committee.	Minimizes labeling effort; maximizes gain.	Needs expert feedback loop.	Targeted species image annotation.	Mendonça *et al.*, 2023; Ren *et al.*, 2022
Federated Learning	Training across distributed datasets without sharing data.	Local datasets at different institutions.	Federated Averaging, Federated Proximal.	Data privacy; collaborative modeling.	Model drift risk; high communication cost.	Cross-country biodiversity monitoring.	Li *et al.*, 2023; Yang *et al.*, 2019; Zhang *et al.*, 2021

Table 1: Innovative machine learning approaches in RS–GIS for biodiversity

Methodology	Description	Data requirements	Typical algorithms / models	Advantages	Limitations	Applications in Biodiversity	Sources
Graph Neural Networks (GNNs)	Modeling spatial and ecological relationships as graphs.	Species occurrence + environmental/spatial data.	Graph Convolutional Networks, Graph Sample and Aggregate, Graph Attention Networks.	Captures species interactions.	Graph construction complexity.	Migration corridor prediction.	Wu *et al.*, 2023, 2021; Zhou *et al.*, 2020
Spatio-Temporal Deep Learning	Models that integrate both spatial and temporal biodiversity patterns.	Multi-timepoint imagery, environmental data.	Convolutional Long Short-Term Memory, Temporal CNN, Transformers.	Captures seasonal/migratory changes.	Computationally heavy.	Seasonal wetland monitoring.	Amato *et al.*, 2020; Wang *et al.*, 2022; Zhang *et al.*, 2020
Hybrid Physics–ML Models	Combining ecological process models with ML predictions.	RS–GIS + ecological simulation outputs.	ML + species distribution models.	Adds interpretability; respects ecology.	Integration complexity.	Climate change impact assessment.	Arcomano *et al.*, 2022; Rai and Sahu, 2020; Willard *et al.*, 2023
Domain Adaptation with Adversarial Training	Aligning feature spaces across domains.	Source + target domain data.	Domain-Adversarial Neural Networks.	Improves generalization.	Training instability.	Sensor-to-sensor habitat mapping.	Fujii *et al.*, 2022; Liang *et al.*, 2023
Reinforcement Learning for Conservation	Optimizing monitoring and conservation strategies.	Historical action-outcome data.	Deep Q-Networks, Policy Gradient.	Adapts to dynamic changes.	Needs accurate simulation.	Patrol route optimization for poaching prevention.	Equihua *et al.*, 2024; Lapeyrolerie *et al.*, 2022
Anomaly Detection with Autoencoders	Identifying deviations from normal patterns.	Historical baseline imagery.	Variational Autoencoders, Deep Autoencoders.	Good for disturbance alerts.	Noise sensitivity.	Detecting forest fires or illegal logging.	Tien *et al.*, 2021; Tziolas *et al.*, 2022
Multi-Modal Learning	Integrating multiple data sources.	Optical, LiDAR, SAR, citizen science.	Fusion CNNs, Transformer fusion models.	Richer, more robust predictions.	Data alignment complexity.	Integrated habitat classification.	Audebert *et al.*, 2018; Wang *et al.*, 2023; Wen *et al.*, 2024
Uncertainty Quantification	Measuring confidence in predictions.	Model predictions + probability outputs.	Bayesian Neural Networks, Monte Carlo Dropout.	Prioritizes reliable outputs.	Can be misleading in noisy data.	Targeting high-certainty species detection for surveys.	Abdullah *et al.*, 2024; Fiedler and Lucia, 2023; Hirsh *et al.*, 2022
Edge AI for Field Monitoring	Running models on field devices.	Compressed model versions + sensor data.	TensorFlow Lite, TinyML.	Enables real-time detection.	Hardware limits.	Drone-based wildlife tracking.	Arashpour, 2023; Kim *et al.*, 2023

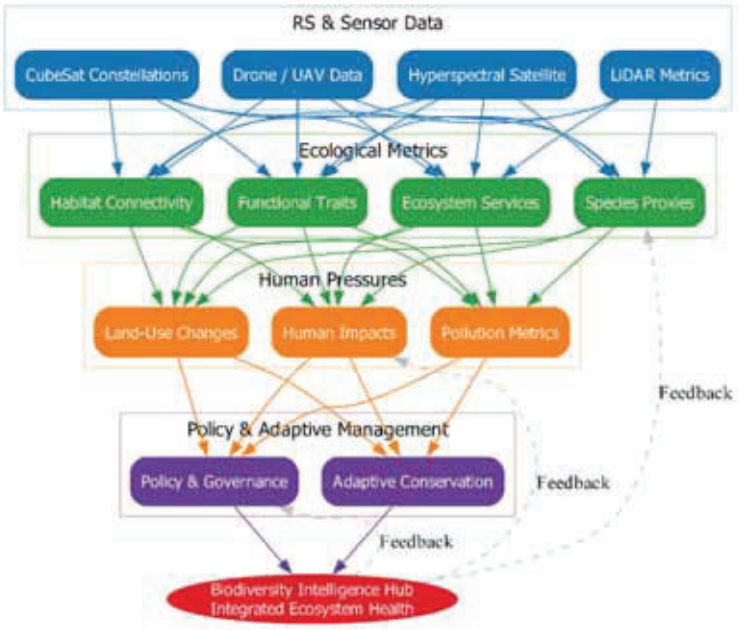

Fig. 5: Multi-dimensional biodiversity intelligence network

for species over time, which is essential for efficient forest management and the preservation of biodiversity. Supporting this approach, Booth (2018), demonstrates that species distribution models (SDMs) have advanced significantly, with correlative SDMs now commonly applied to analyze climate change impacts on more than 50,000 tree species globally. Over 1,000 tree species have been evaluated for anticipated shifts in suitable habitats, demonstrating the increasing ability of SDMs to assist in forest management in light of future climate scenarios. Furthermore, while SDMs are often scrutinized, the limitations identified tend to be less pronounced than commonly asserted, especially when species occurrence data is combined with climatic, soil, and provenance trial data. Importantly, the integration of environmental and species data enhances the accuracy of habitat suitability mapping, facilitating targeted conservation efforts. Complementing this, Anselmetto *et al.* (2025), highlight the value of local-scale species data in improving model performance for current and future species distributions. Their research involving 22 tree species in the Alpine area of Piedmont indicates that SDMs developed using detailed local forest inventories surpassed those based on coarse-scale models, particularly in forecasting future alterations under the RCP4.5 and RCP8.5 climate scenarios. However, they note that models trained on local data may suffer from niche truncation when extrapolating beyond current conditions, which can lead to underestimation or overestimation of range shifts. In a wider biogeographical framework, Franklin (2023) examines three decades of SDM applications and emphasizes their crucial importance in comprehending species distributions across past, present, and future contexts. SDMs are instrumental for delineating ecoregions, assessing biodiversity conservation status, and forecasting species range shifts due to global changes. Issues like defining niches, ensuring data quality, transferring models, and selecting predictors have been increasingly tackled, enhancing the reliability of SDMs for conservation planning. At a landscape scale, García-Amorena *et al.* (2021), combine remote sensing and species distribution modeling to assess the impact of climate change and land use on Pinus hartwegii in Mexico's Izta-Popo National Park. Using 24 Maxent models and Landsat imagery from 1993 and 2013, they reveal significant habitat loss and fragmentation, reducing connectivity and dispersal potential for the species. Projections for 2050 and 2070 under multiple carbon dioxide (CO_2) concentration pathways indicate further

reductions in habitat suitability, with populations likely needing to migrate upslope. Nonetheless, the findings reveal that changes in land use driven by human activity in the past 20 years have concealed some effects of climate change, underscoring the complicated interaction between natural processes and human influences on habitat vulnerability. Table 2 highlights emerging applications of remote sensing (RS) and GIS technologies in advancing biodiversity conservation and ecosystem management.

Monitoring restoration and landscape connectivity

Post-restoration monitoring that incorporates drone-derived data, spectral indices, and LiDAR facilitates the quantification of ecological recovery and functional connectivity. These advanced remote sensing technologies provide high-resolution, scalable, and multidimensional insights into vegetation structure, health, and landscape fragmentation, critical for evaluating restoration success and guiding adaptive management. Robinson *et al.* (2022), emphasize the expanding role of drones in restoration ecology, highlighting their capacity for mapping habitats, tracking restoration progress, and managing disturbances at multiple scales. Considering the anticipated human-induced deterioration of as much as 95% of global ecosystems by 2050, drone technology presents a viable and scalable solution for improving restoration monitoring across the entire restoration process, from planning to execution and continuous evaluation. Their review underscores how drones can significantly improve data collection efficiency and accuracy, essential for meeting ambitious targets such as those set by the United Nations Decade on Ecosystem Restoration. Building on this, Iheaturu *et al.* (2024), demonstrate the power of integrating UAV LiDAR and multispectral data for assessing forest status and disturbance severity in a West African forest patch. By employing principal component analysis, they formulated an integrated disturbance index (IDI) that exceeded the performance of single-sensor methods, reaching a 95% accuracy rate in detecting disturbances. Their findings reveal that nearly 77% of the 560-ha Ewe-Adakplame relict forest faces medium to high disturbance, underscoring the urgency for targeted conservation efforts. Integrating structural LiDAR data with spectral vegetation indices creates a strong foundation for measuring restoration progress and prioritizing interventions for connectivity interventions. Shi *et al.* (2024), further validate the use of combined multispectral remote sensing and laser point cloud monitoring in evaluating vegetation ecological restoration. Applied in China's Daqing oilfield, their approach achieved over 90% monitoring accuracy, revealing a significant vegetation coverage increase of 7,509 km² attributed to farmland conversion to forest.

Urban biodiversity and green infrastructure

Remote sensing and geographic information system applications are gaining importance in urban areas, where they facilitate the planning and implementation of green infrastructure to promote biodiversity, alleviate urban heat, and strengthen ecological connectivity. Czyża and Kowalczyk (2024), demonstrated the use of high-resolution vector data (1 m precision) combined with GIS to identify suitable locations for blue-green infrastructure (BGI) components, including bioswales, infiltration trenches, and green bus stops in Olsztyn, Poland. Their integrative approach combined spatial datasets with a surface urban heat island (SUHI) model and demographic age structure, allowing the identification of priority sites that not only reduce urban heat but also address the social needs of vulnerable populations. This precise spatial modeling aids in the focused deployment of multifunctional green infrastructure, which bolsters ecosystem resilience and enhances the quality of urban life in fast-expanding metropolitan areas. Such comprehensive spatial analyses ensure that blue-green infrastructure is placed effectively to maximize ecological and social benefits in cities. Codemo *et al.* (2022), focused on accurately mapping pervious surfaces and canopy cover to support urban green infrastructure planning through a novel combination of normalized difference vegetation index (NDVI) from airborne imagery at 0.20 m resolution and digital elevation models. Utilized in the Municipality of Trento, Italy, this technique reached an accuracy level greater than 80%, facilitating precise assessment of green space distribution across urban blocks. The resulting maps offer planners detailed insights into areas with deficient canopy or permeable surfaces, essential for guiding interventions that enhance urban climate adaptation and storm water management

Table 2: Emerging applications of remote sensing and GIS in biodiversity conservation

Application area	Description	Potential impact	Key technologies/methods	Current limitations	Examples/use cases	Sources
Climate Change Impact Modeling	Using RS data to model species range shifts, habitat loss, and ecosystem resilience under future scenarios.	Supports anticipatory conservation planning and ecosystem restoration	Satellite climate datasets, species distribution models (SDMs)	Requires integration with complex climate models; uncertainty remains high	Modeling range shifts of forest species under warming	Dubayah *et al.*, 2020; Requena-Mullor *et al.*, 2017; Venter *et al.*, 2020
Invasive Species Early Detection	Combining high-resolution imagery and AI to identify invasive species and monitor spread.	Enables rapid management interventions, reducing ecological damage	Hyperspectral imaging, machine learning classifiers	Difficult to distinguish invasive species spectrally; ground validation needed	Detection of invasive plant species in wetlands	Shafiq *et al.*, 2024; Lake *et al.*, 2022
Wildlife Corridor and Connectivity Mapping	Mapping landscape connectivity and barriers for key species using spatial and movement data.	Facilitates landscape-scale conservation and connectivity planning	GPS telemetry, landscape resistance modeling	Requires multi-source data fusion; temporal dynamics often underrepresented.	Corridor design for big cats in fragmented habitats	Cisneros-Araujo *et al.*, 2021; Martin *et al.*, 2019
Ecosystem Service Monitoring	Linking biodiversity metrics from RS with ecosystem services such as pollination, carbon, and water.	Informs policy and payment for ecosystem services (PES) schemes	Multispectral indices, spatial modeling, economic valuation models	Complex biophysical-socioeconomic integration; data resolution mismatch	Monitoring carbon stocks in tropical forests	Cimoli *et al.*, 2024; Imran *et al.*, 2021
Real-Time Illegal Activity Surveillance	Using satellite, UAV, and sensor networks to monitor poaching, illegal logging, and land-use changes.	Enhances law enforcement and deters biodiversity crimes.	UAVs, sensor networks, automated change detection	Requires frequent data acquisition and rapid analytics; privacy concerns	Anti-poaching patrols in African savannas	Mangewa *et al.*, 2019; Tripathi *et al.*, 2025
Phenology and Seasonal Monitoring	Tracking seasonal changes in vegetation and species behavior to understand ecosystem dynamics.	Supports adaptive management by revealing phenological shifts.	Time-series analysis of satellite data (e.g., NDVI, EVI)	Cloud cover interference; variable temporal resolution	Monitoring flowering times to assess climate impacts	Gong *et al.*, 2024; Surasinghe *et al.*, 2025
Disease and Pest Outbreak Detection	Identifying early signs of disease or pest infestations affecting biodiversity	Enables timely mitigation to protect vulnerable species and habitats.	Thermal imaging, multispectral sensors, AI pattern recognition	Disease symptoms can be spectrally subtle; requires ground truthing	Locust swarm monitoring using remote sensing	Brown *et al.*, 2022; Kariyanna and Sowjanya, 2024
Marine and Coastal Habitat Mapping	Mapping coral reefs, seagrass beds, and mangroves using underwater and surface remote sensing.	Informs marine spatial planning and coastal ecosystem protection.	Multispectral satellite imagery, sonar, UAV surveys	Water turbidity and depth limit detection accuracy	Coral bleaching monitoring in the Great Barrier Reef	Abo Elenin *et al.*, 2020; Siddiqui and Zaidi, 2024
Biodiversity Hotspot Identification	Using multi-sensor RS to identify regions with high species richness or endemism.	Prioritizes conservation areas and resource allocation.	Multispectral, hyperspectral imaging, biodiversity modeling	Spatial resolution may miss microhabitats; requires field validation	Identifying Amazonian hotspots for protection	Marchese, 2015; Wu and Liang, 2018
Carbon and Biomass Estimation	Estimating forest biomass and carbon stocks as proxies for ecosystem health.	Supports climate mitigation strategies and REDD+ programs.	LiDAR, RAdio Detection and Ranging, multispectral imaging	High cost and processing demands; variable accuracy in dense forests	Estimating carbon stocks in boreal forests	Chinembiri *et al.*, 2024; Ranglong *et al.*, 2025
Landscape Disturbance and Recovery Monitoring	Detecting natural or anthropogenic disturbances and tracking ecosystem recovery over time.	Assesses conservation effectiveness and guides restoration efforts.	Time-series satellite imagery, change detection algorithms	Distinguishing natural from human-induced changes can be complex	Monitoring forest regrowth after fire events	Ren *et al.*, 2023; Tan *et al.*, 2024
Species Distribution and Habitat Suitability Modeling	Predicting spatial distribution of species based on habitat variables derived from RS data.	Supports targeted species conservation and habitat management.	GIS-based habitat models, machine learning, environmental layers	Model uncertainty; lack of fine-scale data for rare species	Habitat suitability for endangered amphibians	Dastres *et al.*, 2025; Rew *et al.*, 2020

Socio-ecological integration and ethical dimensions

Inclusion of indigenous and local knowledge

Participatory geographic information systems (PGIS) have become crucial tools for integrating indigenous and local knowledge into natural resource management and land use planning, especially in contexts such as rangeland management in Africa. Azong Cho and Mutanga (2021), reviewed PGIS applications in African rangeland use planning and highlighted how PGIS facilitates the capture of diverse local actors' perspectives, contributing to more inclusive and culturally relevant decision-making processes. While PGIS offers promising opportunities for the inclusion of community insights, it still faces challenges, including issues related to content quality, methodological rigor, representation, equity, and access to technology. The study highlights that while PGIS can enhance the empowerment of local communities by allowing them to map and convey their resource utilization and priorities, advantages are frequently obstructed by inconsistent participation and ongoing power disparities. The tourism industry also increasingly leverages public participation geographic information systems (PPGIS) to enhance community involvement in planning and decision-making, ensuring that development is economically viable, environmentally responsible, and socially inclusive. Gheitasi, Salari, and Clark (2024), conducted a comprehensive review of PPGIS use in tourism from 2000 to 2024, identifying that PPGIS provides a credible and flexible alternative to traditional public engagement methods such as meetings and interviews. The research indicated that PPGIS allows stakeholders, such as residents and local businesses, to spatially articulate their concerns and preferences, resulting in more informed and community-focused tourism planning. This digital, geospatial approach supports sustainable tourism by capturing nuanced local knowledge and values, facilitating transparent communication, and increasing the inclusiveness of planning processes. Beyond sector-specific applications, the broader academic landscape of Public Participation GIS (PPGIS) research has evolved substantially since the 1990s, as detailed by Mohamed (2025). In Table 3, key features of stakeholder engagement and the integration of social dimensions into biodiversity monitoring and conservation efforts are summarized.

Data sovereignty and governance

Ensuring data sovereignty in open-access conservation platforms involves more than simply controlling where data is stored; it requires clear frameworks that define ownership rights, usage boundaries, and the responsibilities of all actors involved. Without proper governance, there is a risk that sensitive ecological or community information could be misappropriated, which would weaken trust and dissuade involvement from important stakeholders. This is particularly critical in conservation contexts where data often relates to endangered species locations, indigenous territories, or vulnerable habitats. In these situations, misuse could lead to ecological harm or social exploitation. Supporting this, Brodny and Tutak (2025), emphasize that without robust ethical integration in technological systems, even innovations that are well-intentioned may jeopardize privacy and undermine public trust. Their work shows that transparent stakeholder engagement is essential for balancing technological advancement with the protection of fundamental rights. Governance frameworks should also tackle the imbalanced power dynamics present in AI-driven conservation efforts, guaranteeing that advantages are equitably distributed and that marginalized communities are included in the decision-making process. This includes creating equitable access to AI tools, transparent data-sharing agreements, and mechanisms to challenge misuse or bias. In the context of higher education, Balan (2024), emphasizes that sustainable AI integration requires equity-focused policies, proactive bias mitigation, and inclusive governance structures.

Monitoring for environmental justice

Monitoring for environmental justice through RS–GIS tools requires more than simply mapping physical environmental parameters; it demands a spatially explicit approach that integrates socio-economic vulnerability, ecological stressors, and governance priorities to identify inequality hotspots and guide targeted interventions. Furthermore, without these frameworks, the allocation of resources could remain unaware of the layered challenges that marginalized groups encounter, thus sustaining current disparities. Evidence from Tanzania demonstrates by Macharia *et al.* (2020), combined biophysical and socio-economic

Table 3: Stakeholder engagement and social dimensions in biodiversity monitoring

Aspect	Description	Benefits	Challenges	Key Stakeholders	Implementation Examples	Success Factors	Sources
Incorporation of Traditional Ecological Knowledge (TEK)	Integrating indigenous and local ecological knowledge systems with modern monitoring tools.	Provides context-rich insights; improves monitoring relevance; strengthens cultural identity.	Cultural sensitivity; protecting intellectual property rights; potential mistrust.	Indigenous communities, elders, cultural heritage bodies, ecologists.	Arctic biodiversity monitoring using Inuit knowledge; Amazon forest mapping with tribal input.	Trust-building, equitable data-sharing agreements, recognition of intellectual property.	Bwambale *et al.*, 2018; Singleton *et al.*, 2023
Community-Based Monitoring (CBM)	Local communities actively collect and interpret biodiversity data.	Builds local capacity; fosters stewardship; enables rapid detection of changes.	Ensuring data quality; sustaining long-term participation; avoiding volunteer fatigue.	Local NGOs, residents, schools, conservation agencies.	Reef monitoring by coastal villages; forest patrols by community rangers in Africa.	Continuous training, incentives, feedback loops, clear communication of impact.	Chandler *et al.*, 2017; Price *et al.*, 2023; Shephard *et al.*, 2023
Open Data and Citizen Science Platforms	Publicly accessible biodiversity data portals and apps enabling citizen participation.	Expands spatial/temporal coverage; democratizes science; fosters transparency.	Data verification; digital divide; varying skill levels among contributors.	General public, tech developers, universities, conservation agencies.	iNaturalist, eBird, Global Biodiversity Information Facility (GBIF).	Robust data validation, user-friendly platforms, offline data collection options.	Serbe-Kamp *et al.*, 2023; Ziliaskopoulos and Laspidou, 2024
Policy Integration and Adaptive Management	Linking monitoring outputs with governance and adaptive policy frameworks.	Enables responsive conservation; supports evidence-based decision-making.	Bureaucratic inertia; conflicting stakeholder priorities; slow policy cycles.	Government ministries, policy-makers, NGOs, researchers.	European Union Habitats Directive reporting; adaptive wildlife corridor management.	Cross-sector coordination, policy champions, legal mandates for monitoring data use.	Armstrong and Kamieniecki, 2017
Cross-Border Biodiversity Collaboration	Shared monitoring and conservation efforts across political boundaries.	Protects migratory species; improves regional ecosystem resilience.	Political tensions; harmonizing methodologies; data sovereignty issues.	Neighboring governments, transboundary conservation groups, intergovernmental bodies.	Great Limpopo Transfrontier Park wildlife tracking; Mekong River fish monitoring.	Diplomatic agreements, standardized protocols, shared funding.	Kotru *et al.*, 2020; Magory Cohen *et al.*, 2022
Private Sector Engagement	Partnering with industries for biodiversity data sharing and sustainable practices.	Access to new data sources (e.g., corporate landholdings); co-funding opportunities.	Conflicts of interest; greenwashing risks; transparency issues.	Agribusiness, mining companies, tourism operators.	Biodiversity offsets by mining companies; wildlife-friendly farming certifications.	Clear agreements, independent oversight, long-term sustainability commitments.	Ackers and Adebayo, 2024
Education and Awareness Campaigns	Using biodiversity monitoring outcomes to inform and educate.	Builds public support; inspires conservation action.	Over-simplification risk; competing public priorities.	Schools, media outlets, NGOs.	Public campaigns on pollinator declines; youth biodiversity clubs.	Engaging storytelling, culturally relevant content, multi-platform outreach.	Ardoin *et al.*, 2020; Banha *et al.*, 2022
Participatory Mapping and GIS Storytelling	Co-creating maps and spatial narratives with stakeholders.	Encourages local ownership; improves data accuracy with lived experience.	Potential disagreements on territorial boundaries; data sensitivity.	Local communities, GIS experts, advocacy groups.	Participatory wetland mapping in South America; indigenous land rights mapping in Canada.	Inclusive facilitation, accessible map tools, respect for confidentiality.	Onencan *et al.*, 2018; Weyer *et al.*, 2019

indicators to produce climate vulnerability index maps for the Wami-Ruvu and Rufiji basins, revealing concentrated "hotspot" communities where water scarcity, climate variability, and population growth intersect to intensify risk. These spatial outputs were employed directly to prioritize measures for adaptation and to bolster local institutional capacity, illustrating how geospatial analysis can move beyond diagnosis to actionable resilience planning. Similarly, Boori *et al.* (2022), applied a DPSIR-based ecological vulnerability index in Russia's Republic of Tatarstan, integrating 23 indicators from satellite, socio-economic, and demographic data to capture the cumulative pressures of industrialization and environmental degradation.

Data integration and standardization

Harmonizing heterogeneous multi-sensor and multi-resolution remote sensing datasets remains a critical challenge for advancing biodiversity monitoring. Differences in spatial, spectral, and temporal resolutions, as well as varying sensor characteristics and coordinate systems, may cause inconsistencies that obscure ecological signals unless they are meticulously handled. Developing standardized pre-processing workflows, calibration protocols, and cross-sensor harmonization techniques is essential to ensure that the ecological integrity of the data is preserved while enabling meaningful comparisons across studies and ecosystems (Aguzzi *et al.*, 2025). It is equally vital to standardize RS-derived indicators that assess habitat quality and ecosystem function. Scaling locally validated RS/GIS methodologies to global applications presents additional complexity, as models trained in specific ecological contexts may not generalize without introducing oversimplification (Markham *et al.*, 2023).

Biodiversity detection and measurement

Remote sensing has significantly progressed in the mapping of habitats and the evaluation of ecosystem-level patterns; however, identifying cryptic or rare species continues to be a persistent challenge. The inherent spatial and spectral limitations of many sensors mean that individuals or low-density populations can be overlooked, potentially underestimating biodiversity. Integrating remote sensing with complementary approaches, such as environmental deoxyribonucleic acid (eDNA) sampling and bio-logging, can bridge this gap. eDNA provides species-level detection without direct observation, while bio-logging tracks individual movements and behaviors (Li *et al.*, 2024). When these approaches are paired with high-resolution spatial data, they create a more comprehensive and accurate representation of biodiversity distribution, particularly for elusive or nocturnal species. Moving beyond habitat proxies toward direct measurements of functional, trait, and genetic diversity represents a critical frontier in RS applications. Hyperspectral imaging, structural metrics derived from LiDAR, and observations from drones can detect fine differences in leaf chemistry, canopy structure, and species compositions that indicate functional characteristics (Shu *et al.*, 2025). Trait-based indicators can be connected to ecosystem processes, which allows researchers to derive biodiversity function rather than relying only on surrogate habitat metrics. Incorporating genetic or phylogenetic information, either through eDNA or trait-environment correlations, further enhances the ecological interpretability of remotely sensed data, providing a more mechanistic understanding of ecosystem dynamics (Bauknecht *et al.*, 2025). Identifying invasive species at an early stage is yet another crucial application in which next-generation RS exhibits promise. Hyperspectral sensors, coupled with drone platforms, can identify subtle spectral anomalies or morphological signatures indicative of emerging invasive populations (Karahan *et al.*, 2025). Integrating these early-warning detections with prompt response measures, including targeted management interventions or alert systems, can notably decrease ecological and economic impacts. Such integration requires automated change detection, real-time processing, and seamless communication between monitoring and management frameworks. The latest remote sensing technologies also provide the potential to advance fine-scale models of species distribution and habitat suitability. By integrating multi-temporal and multi-resolution datasets with ecological niche modeling, researchers can dynamically update predictions for both endangered and invasive species in response to environmental change (Devika and Amitha Bachan, 2025).

Forecasting and early-warning systems

Remote sensing and GIS are progressively being

seen not merely as tools for observing biodiversity, but also as systems for anticipating ecological transformations under various climate and land-use conditions. By integrating multi-temporal and multi-resolution datasets with predictive modeling frameworks, RS/GIS can anticipate shifts in species distributions, habitat quality, and ecosystem functioning, enabling proactive management interventions (Bin *et al.*, 2025). Near-real-time data streams assist in the development of early-warning systems that can detect emerging threats, ecological tipping points, or potential regime shifts ahead of irreversible damage. Time-series analyses of satellite and drone-derived observations can be optimized to disentangle climate-driven variability from anthropogenic pressures, improving the reliability of forecasts (Inoue, 2020). RS-derived phenological indicators, such as leaf-out timing, flowering, or migration cues, can be linked to species interactions to identify potential ecological mismatches under changing climates, while coupled vegetation; climate models allow for the prediction of feedback loops that influence ecosystem resilience (Renner and Zohner, 2018). Employing GIS to provide spatial context to these dynamics facilitates the detection and modeling of vital recovery thresholds, tipping points, and regime shifts in complex ecosystems (Dakos *et al.*, 2024).

Ecosystem functions, networks, and services

Remote sensing and GIS provide powerful tools for moving beyond static habitat mapping to capture the dynamic integrity of ecological networks, including habitat connectivity, trophic interactions, and pollination systems. By merging multi-source data including LiDAR, radar, and optical imagery, RS techniques are capable of quantifying structural and functional connectivity, observing changes in wildlife corridors over time, and validating these trends with genetic flow data to ensure ecological authenticity (Neumann *et al.*, 2015). Linking biodiversity metrics with ecosystem service assessments enables spatially explicit evaluation of provisioning, regulating, and supporting services, informing conservation prioritization and landscape management decisions (Ramel *et al.*, 2020). By merging LiDAR, radar, and optical datasets facilitates accurate estimations of biomass and carbon stocks both above and below ground, effectively aligning biodiversity monitoring with climate mitigation efforts (Luo *et al.*, 2017). Advanced time-series analyses and change-detection algorithms can identify subtle or cumulative disturbances, monitor successional pathways, and differentiate between natural variability and anthropogenic influences, aiding inrestoration and recovery efforts. Furthermore, deep-learning-enabled analysis of high-resolution RS imagery has the potential to uncover previously unknown biodiversity hotspots or ecological corridors that are not captured by field-based surveys, thereby expanding the scope and effectiveness of conservation planning (Pettorelli *et al.*, 2025).

Analytical and computational innovations

Next-generation remote sensing technologies, including hyperspectral sensors, LiDAR, radar, small satellite constellations, and drones, are dramatically enhancing biodiversity and ecosystem monitoring capabilities by providing high-resolution, multi-dimensional, and temporally continuous data. These sensors provide the capability for detailed mapping of species distributions, habitat structures, and ecosystem functions at extraordinary scales, which helps in recognizing subtle ecological variations and patterns that have not been previously documented. Machine learning and deep learning models offer powerful analytical frameworks for processing these complex datasets, but ensuring transparency, interpretability, and freedom from algorithmic bias is essential for their reliable application in conservation (Patil *et al.*, 2024). Implementing explainable AI strategies, assessing uncertainty, and ensuring rigorous model validation are crucial for building confidence among practitioners and policymakers (Mersha *et al.*, 2024).

Governance, access, and ethics

Remote sensing and GIS-based biodiversity monitoring systems offer unprecedented opportunities to empower Indigenous and local communities while safeguarding cultural sovereignty and intellectual property rights. Collaborating with these stakeholders to co-develop monitoring frameworks allows data collection and interpretation to align with local knowledge systems and priorities, thereby promoting ownership, trust, and equitable benefit-sharing (Ćwikła *et al.*, 2025). Real-time RS-based surveillance can enhance conservation

enforcement by detecting illegal activities such as logging, mining, or poaching, yet these systems must be designed to respect privacy and sovereignty, ensuring that monitoring does not inadvertently infringe upon community rights (Wang *et al.*, 2025). Additionally, RS/GIS workflows present strong and consistent indicators that can facilitate global biodiversity accounting frameworks and national reporting obligations, including the Sustainable Development Goals and the Kunming–Montreal Global Biodiversity Framework.

Challenges and knowledge gaps

One of the most urgent challenges in applying RS and machine learning (ML) to biodiversity monitoring is the limited availability of ground-truthed biodiversity indicators for algorithm training. Furthermore, lacking comprehensive in situ datasets can cause predictive models to misidentify habitats or miss subtle ecological shifts, potentially leading to erroneous conservation choices. Field validation remains essential for refining models and ensuring that automated classifications accurately reflect ecological conditions on the ground. For instance, Kovárník and Janová (2025) demonstrated that validating Sentinel-2-based ML models with National Forest Inventory data significantly improves model accuracy, achieving up to 98.3% in land cover estimation. A further important issue is the undue reliance on proxy metrics, including spectral indices, instead of relying on direct ecological observations. Furthermore, while NDVI can indicate broad patterns, it can also overlook the complexities of ecological variability in complex environments. Pinon *et al.* (2024) highlighted that although spectral diversity correlates strongly with species richness and diversity in the Brazilian Atlantic Forest, factors such as pixel size and shadow effects influence these relationships, underscoring the need to integrate spectral proxies with field-based observations for a more comprehensive understanding of biodiversity dynamics. The significant computational requirements for handling multi-source RS data pose a short-term challenge, which is becoming more manageable with contemporary workflows. Integrating hyperspectral, LiDAR, radar, and multispectral datasets requires cloud-based platforms and specialized algorithms capable of handling petabyte-scale inputs. Prošek *et al.* (2020) showed that combining hyperspectral and LiDAR data significantly improves classification accuracy, particularly for small water bodies, with omission and commission errors below 10%. These findings highlight that adopting advanced computational workflows can mitigate processing challenges in the near term. Likewise, challenges related to interoperability differing sensor formats, spatial resolutions, and coordinate systems make it difficult to achieve seamless integration of datasets sourced from multiple origins. Differences in temporal coverage, geodetic reference frames, and preprocessing requirements increase operational costs and the risk of analytical errors. In conclusion, limitations in satellite sensor capabilities present an ongoing challenge for biodiversity observation. Often, current sensors are deficient in the integrated spatial, spectral, radiometric, and temporal resolutions required to accurately capture swiftly changing ecological variables, particularly in dynamic coastal environments. Muller-Karger *et al.* (2018) emphasize the need for a new generation of satellites with enhanced specifications, referred to as H4 imaging, to improve data consistency and interoperability.

Future frontiers and research directions

The integration of eco-acoustics and bio-logging data into remote sensing and GIS platforms offers a significant advancement in biodiversity monitoring. By combining environmental audio recordings with spatial data on species movement, researchers can obtain a richer, multidimensional perspective of ecosystems. This technique enhances the ability to identify elusive or nocturnal species that are frequently overlooked by standard remote sensing methods, improving both the range and accuracy of biodiversity evaluations. Farina (2018) notes that ecoacoustics provides quantitative metrics that serve as proxies for biodiversity and ecosystem health, supporting both field-based and remote surveys while enabling long-term monitoring across multiple spatial and temporal scales. Combining these datasets with information obtained from satellites can improve predictive modeling, especially in regions where data is scarce, by identifying ecological variability that purely spectral metrics could fail to recognize. Developing near-real-time biodiversity observatories using edge artificial intelligence and in-situ sensors represents another frontier. Processing data locally at sensor sites reduces latency and bandwidth requirements,

enabling the rapid detection of emerging threats such as invasive species, habitat degradation, or sudden population declines. This forward-thinking monitoring method can boost conservation responsiveness and adaptive management. Ditria *et al.* (2022) highlight that AI-driven automated monitoring addresses key challenges in conservation, including limited funding, workforce constraints, and bottlenecks in data processing, thereby facilitating timely access to comprehensive information for informed decision-making. Kovari (2024) points out that achieving a balance between transparency, accuracy, and trust is essential for the successful implementation of AI-based decision support systems across different industries. Explainable AI enables stakeholders to assess uncertainties, evaluate risks, and adopt interventions with greater confidence, ultimately improving the effectiveness of technology-guided conservation strategies. Some proposed innovations extend beyond RS–GIS and AI to cross-disciplinary approaches. The combination of biodiversity monitoring and economic models, including biodiversity credits, is an innovative approach that connects ecological results to financial rewards. Integrating spatial biodiversity data with market-based mechanisms can help prioritize conservation investments toward interventions with the highest ecological impact. Wunder *et al.* (2025) report that biodiversity credits offer potential for enhancing pro-environmental behavior, although challenges remain in their design, governance, and impact evaluation. Co-designing monitoring systems with local stakeholders, including communities, indigenous groups, and land managers, is vital for long-term sustainability and relevance.

Future research priorities

- Develop integrated RS–GIS platforms that combine eco-acoustic, bio-logging, and satellite data to enable multidimensional and high-resolution biodiversity monitoring;
- Develop advanced AI technologies and automated, near-real-time observatories to facilitate improved early detection of ecological risks and alleviate data processing bottlenecks;
- Enhance AI explainability and transparency to ensure practitioner trust, informed decision-making, and ethical deployment in conservation;
- Explore cross-disciplinary approaches, such as biodiversity credits, ensuring robust monitoring and governance frameworks to link ecological outcomes with policy and economic incentives;
- Engage local stakeholders through participatory co-design methods to improve the relevance, accessibility, and sustainability of monitoring systems over time.

CONCLUSION

The integration of remote sensing and geographic information systems has become increasingly indispensable for biodiversity monitoring and ecosystem management under accelerating climate change, land-use transformations, and other anthropogenic pressures. This review specifically underscores the unique contributions of emerging RS–GIS technologies to the discipline, transcending a basic summary of tools to illustrate how these innovations are altering ecological science and conservation practice. By combining multi-sensor data fusion, advanced machine learning and deep learning frameworks, and participatory monitoring approaches, RS–GIS applications now enable the generation of high-resolution, temporally continuous, and spatially explicit datasets. These datasets deliver exceptional understanding of biodiversity dynamics, functional characteristics, and ecosystem processes at various scales; local, regional, and global; equipping conservation practitioners and policymakers with actionable intelligence. Recent advancements, including hyperspectral imaging, drone-based sensing, radar interferometry, and CubeSat constellations, have significantly enhanced the ability to detect fine-scale ecological patterns, species distributions, and habitat changes in near real-time. When coupled with analytical tools such as convolutional neural networks, transfer learning, and cloud-based geospatial platforms, these technologies facilitate automated classification, ecosystem change forecasting, and detection of subtle phenological and landscape-level shifts that were previously undetectable. Moreover, the incorporation of multi-temporal and multi-resolution datasets improves the ability to monitor ecological processes, evaluate connectivity, and observe environmental changes with greater accuracy, thereby guiding focused management strategies. Despite these transformative capabilities, persistent challenges limit the full operationalization of RS–GIS in biodiversity science. The scarcity of ground-truthed

biodiversity information hampers the calibration and validation of models, which in turn creates in ecological predictions. Interoperability issues among heterogeneous sensors, platforms, and analytical frameworks complicate data integration, while reliance on proxy variables such as vegetation indices can reduce ecological interpretability. High computational requirements and the unavailability of accessible high-performance infrastructure continue to hinder large-scale analyses, particularly in regions with low and middle incomes. Beyond technical considerations, ethical, social, and governance challenges, including data sovereignty, equitable benefit-sharing, and inclusion of indigenous and community knowledge, remain critical for ensuring socially just and globally relevant monitoring systems. This review underscores several actionable priorities for advancing RS–GIS applications in biodiversity science. Integrative frameworks that combine remote sensing technologies with in-situ ecological observations, citizen science contributions, contributions from citizen science, and engagement with local stakeholders are crucial for enhancing the accuracy and relevance of models. Expanded field-based validation campaigns and open-access, interoperable platforms will democratize the use of RS–GIS tools, enabling broader participation in ecological monitoring. Developing effective data governance systems that harmonize transparency, security, and inclusivity is crucial for the long-term application of these technologies. By addressing both technical and socio-ecological challenges, RS–GIS can become a foundational component of global biodiversity intelligence, supporting evidence-based conservation strategies, adaptive management, and proactive policy formulation. The use of RS–GIS applications will enhance the recording of ongoing biodiversity changes while also delivering actionable insights that can reinforce ecosystem resilience, protect essential habitats, and ensure the long-term sustainability of life-support systems on which human well-being depends. This review contributes to the field by outlining practical pathways for integrating technological, ecological, and societal dimensions, enabling the development of predictive, equitable, and impactful biodiversity monitoring systems.

AUTHOR CONTRIBUTIONS

A. Zhidebayeva conceptualized the review framework, coordinated the overall structure, and contributed to drafting and editing the manuscript. S. Syrlybekkyzy conducted an extensive literature search, performed data extraction, and contributed to synthesizing key findings. L. Taizhanova organized and analyzed the reviewed literature, prepared summary tables, and assisted in drafting the methodology and results synthesis. S. Koibakova contributed to the selection and critical evaluation of relevant studies and assisted in preparing figures and visualizations. Z. Altybaeva supported the literature review process, compiled supporting references, and assisted in drafting the discussion section. A. Koishina participated in structuring the manuscript, reviewed emerging trends, and assisted in finalizing the conclusions. L. Seidaliyeva contributed to summarizing recent advancements, refined the narrative flow, and critically reviewed the manuscript draft. T. Mkilima, the corresponding author, conceived the review idea, supervised the entire process, integrated contributions from all authors, critically revised the manuscript, and finalized it for submission.

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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.

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Negative AI Statement

The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Per cent
AI	Artificial intelligence
BGI	Blue-green infrastructure
CICDDOS 2019	Canadian Institute for Cybersecurity Distributed Denial of Service 2019 Dataset
CIgreen	Green chlorophyll index
CIred edge	Red-edge chlorophyll index
CNNs	Convolutional Neural Networks
CO_2	Carbon dioxide
CubeSat	Cube Satellite
CWC	Canopy water content
DL	Deep learning
eDNA	Environmental deoxyribonucleic acid
e.g.	Exempli gratia/ for example
EnMAP	Environmental Mapping and Analysis Program
ESIS	Earth sensing imaging spectrometer
EVI	Enhanced vegetation index
EWT	Equivalent water thickness
Fig.	Figure
GEDI	Global ecosystem dynamics investigation
GIS	Geographical information system
GVMI	Global vegetation moisture index
IDI	Integrated disturbance index
LFMC	Live fuel moisture content
LiDAR	Light detection and ranging
LSWI	Land surface water index
ML	Machine learning
MSI	Moisture stress index
NDII	Normalized difference infrared index
NDVI	Normalized difference vegetation index
NDWI	Normalized difference water index
NIR	Near-infrared
NRred edge	Red edge normalized ratio
PGIS	Participatory geographic information systems
PRISMA	PRecursore IperSpettrale della Missione Applicativa
PRI	Photochemical reflectance index
RNN	Recurrent neural network
RS	Remote sensing
SAR	Synthetic aperture radar
SAVI	Soil adjusted vegetation index
SUHI	Surface urban heat island
SWIR	Shortwave infrared
SVM	Support vector machines
T/ha	Ton per hectare
UAVs	Unmanned aerial vehicles
XAI	Explainable AI

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REVIEW PAPER

Bibliometric and narrative review of environmental management on green behavior education for sustainable development

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Sustainability governance

ABSTRACT

Studies on environmentally friendly practices in education have grown significantly due to global sustainability issues, but thorough reviews that combine bibliometric mapping with conceptual analysis are still limited. The study objectives were to analyze global scholarly output on green behavior and education for sustainable development. It also assessed how this field connects to sustainability governance and environmental management strategies. The study analyzes worldwide academic contributions to education for sustainable development and environmentally friendly practices by integrating bibliometric analysis with a narrative synthesis of significant studies. A total of 330 peer-reviewed articles published between 2008 and 2025 in the Web of Science database were analyzed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 guidelines. Biblioshiny and CiteSpace software were employed to examine publication trends, collaboration networks, citation patterns, and thematic clusters, while highly cited and representative studies were synthesized to clarify methodological approaches, theoretical insights, and policy relevance. The results show an annual growth rate of 25.26 percent since 2016 across 111 journals, with a significant contribution from advanced economies, while participation from developing regions is gradually on the rise. There has been a rise in international collaboration, which now constitutes 31.5 percent of publications, yet there are still imbalances in research capacity. Three core dimensions consistently emerge: organizational drivers such as green human resource management, organizational citizenship behavior for the environment, and transformational leadership; individual factors including attitudes, social norms, and behavioral intentions; and systemic conditions encompassing consumer education, green marketing, and sustainable consumption. Narrative evidence illustrates the significance of leadership, behavioral interventions, and supportive policy frameworks in fostering sustainability outcomes. The review illustrates that education focused on sustainable development promotes green behavior, which plays a crucial role in advancing environmental management and governance. Additionally, emphasizes the significance of theoretical frameworks including the theory of planned behavior, the value–belief–norm model, and the technology acceptance model. Nonetheless, integrative approaches remain limited, and gaps persist in contributions from developing regions, adoption of digital innovation, and comparative cross-country studies. The study indicates that integrating sustainability principles into education is a long-term investment in human capital and serves as a catalyst for collective environmental change, providing evidence-based recommendations for future studies, institutional practices, and policy formulation.

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INTRODUCTION

In recent decades, education for sustainable development (ESD) has become central to higher education policy, addressing global challenges such as climate change, environmental degradation, and inequality (Wals, 2014; Lozano *et al.,* 2015; Wiek *et al.,* 2011; UNESCO, 2020). ESD is intricately connected to sustainable practices, defined as conscious efforts to minimizing environmental effect and preserve ecological equilibrium (Peattie and Crane, 2005; Gifford and Nilsson, 2014). This shift positions universities to produce environmentally literate graduates able to lead sustainability transitions (Wals, 2014; Barth and Rieckmann, 2012; Holdsworth *et al.,* 2018; Wu and Shen, 2016). Institutions operate as vibrant laboratories, promoting waste reduction, carbon mitigation, and resource efficiency (Evans *et al*., 2016; Sulphey *et al.,* 2024; Herth *et al*., 2025). The relationship between ESD and green behavior has gained visibility in business, economics, and the social sciences. Courses in business schools that emphasize sustainability shape ethical decision-making and foster green entrepreneurship among future leaders (Lambrechts *et al.,* 2013; Abo-Khalil, 2024). Social science approaches highlight cultural norms, collective identity, and global citizenship as pathways to sustainable lifestyles (Monzó-Martínez *et al.,* 2024; Reysen and Katzarska-Miller, 2013; Geng *et al.,* 2017). Studies on leadership emphasizes the critical role of both green transformational and transactional leadership in fostering innovation (Saif *et al.,* 2023; Robertson and Barling, 2013; Mittal and Dhar, 2016). Other empirical work shows that environmental awareness and green human resource management shape organizational practices. Citizen participation improves urban water management (Mardianti and Purba, 2023), while green human resource management (GHRM) enhances employees' environmental performance (Kuo *et al.,* 2022). The behavior of voluntary organizational citizenship also bolsters environmental management (Sulphey *et al*., 2024). In recent times, eco-spiritual viewpoints have enriched the conversation by associating profound motivational influences with pro-environmental actions (Elneel Adow, 2024). At a local level, Wijaya and Kokchang (2023) found that environmental awareness and concern have a positive influence on Generation Z's attitude towards the energy transition. This upgraded perspective, combined with perceived behavioral control, notably strengthens their intention to endorse the energy transition, which in turn promotes more vigorous pro-environmental conduct. Moreover, bibliometric evidence from the Global Journal of Environmental Science and Management (Sulphey *et al.,* 2024) shows that Organizational Citizenship Behavior for the Environment (OCBE) has emerged as a distinct thematic cluster within sustainability science. The study highlights how voluntary and proactive environmental behaviors, particularly within organizational and educational settings, contribute to improved environmental management and sustainability outcomes (Filho *et al.,* 2018; Boström *et al*., 2018). This alignment between educational, economic, and environmental sectors indicates a transition towards comprehensive governance frameworks and facilitates the development of scalable solutions in green entrepreneurship and sustainable consumption (Murga-Menoyo, 2015; Brzyska *et al.,* 2023). Furthermore, this study utilizes a narrative synthesis of significant publications beyond mere descriptive mapping to clarify their theoretical, methodological, and practical contributions. In addition to descriptive mapping, this research employs a narrative synthesis of key publications to elucidate their theoretical, methodological, and practical contributions (Yang *et al.,* 2023; Xiao and Watson, 2019). By integrating bibliometric mapping with structured synthesis, this study combines quantitative and qualitative insights, bolsters theoretical foundations, uncovers gaps, and develops a research agenda that connects education, management, and sustainability governance (Lozano *et al.,* 2013; Tafese and Kopp, 2025). The study addresses five questions: 1) What is the annual and geographical distribution of research on green behavior and education for sustainability? 2) Who are the leading contributors, including authors, journals, and institutions? 3) What dominant themes define the relationship between ESD and sustainable behavior? 4) How do influential studies contribute theoretically, methodologically, and practically? 5) What gaps and future directions can inform sustainability governance and policy? The objective of this study is to deliver an extensive review of international research concerning green behavior in education, by identifying trends and clusters, while also emphasizing existing gaps and potential future directions. This study was conducted in Bandung, Indonesia in 2025.

METHODOLOGY

The study design

This study applies a quantitative bibliometric mapping approach to examine research trends in green behavior and education for sustainability, focusing on authorship, publications, keywords, journals, countries, and citation patterns (Goksu, 2021; Kemeç and Altınay, 2023). The method consisted of selecting a bibliographic database, setting search criteria, and utilizing analysis software (Gao *et al.,* 2022; Liu *et al.,* 2025). The Web of Science has been identified as the key source because of its rigorous peer-review standards, extensive multidisciplinary scope, and transparency in bibliographic data (Singh *et al.,* 2021; Pranckutė, 2021; Gusenbauer, 2024). The applied search query was as follows:

TITLE-ABS-KEY: ((“green behavior” OR “pro-environmental behavior” OR “sustainable behavior”) AND (“education” OR “learning” OR “curriculum” OR “environmental education” OR “global citizenship”) AND (“sustainability” OR “climate change” OR “ESD” OR “education for sustainable development”)

The review encompassed publications from 2008 to 2025, focusing exclusively on English-language articles in the fields of management, economics, business, social sciences, and environmental sciences. Biblioshiny and CiteSpace were used for quantitative analysis, network visualization, and thematic mapping (Erlande *et al.,* 2025; Adithya *et al.,* 2025; Umar *et al.,* 2024), enabling the examination of conceptual structures, intellectual linkages, and emerging themes in green behavior and sustainability education. To uphold methodological integrity, predetermined inclusion and exclusion criteria were utilized related to timespan, document type, subject area, and language, as indicated in Table 1.

Assessing article characteristics

The subsequent phase involves performing a bibliometric analysis of the qualifying papers after the selection process has been finalized according to the inclusion and exclusion criteria. This study map thematic developments, productivity trends, patterns of collaboration, Green behaviour and sustainability education. Data and visual representations are displayed in the form of graphs, tables, and network maps generated through bibliometric software. Table 2 outlines the primary bibliometric parameters investigated in this study, which encompasses the distribution of publication years, the leading authors and institutions in terms of productivity, the articles that are cited most often, keyword co-occurrence networks, and the thematic clusters that prevail in the research landscape.

Data collection

This study used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to guide the data collection process. PRISMA improves transparency and replicability by structuring the review into four stages: identification, screening, eligibility, and inclusion, as illustrated in Figure 1. Its implementation improved methodological precision and reduced bias by recording every phase of article selection (Page *et al.,* 2021). However, PRISMA was originally developed for clinical and medical reviews, which limits its ability to address citation quality or interdisciplinary spread in bibliometric studies. Despite this, it provided greater clarity and consistency in reporting, which rendered the findings more dependable and reproducible.

The PRISMA diagram above shows the document selection process from the 520 articles identified from the Web of Science database. Two hundred ninety documents were eliminated based on document type (49) and field of study (241). After the screening and eligibility checking process, no further documents were excluded. The final result, 330 papers met the criteria and were analyzed in this study.

Table 1: Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Timespan	2008–2025	Articles before 2008 or after 2025
Document type	Peer-reviewed journal article	Books, book chapters, proceedings, reviews
Subject area	Management, economics, business, social science, environmental science	Outside these disciplines
Language	English	Non-english articles

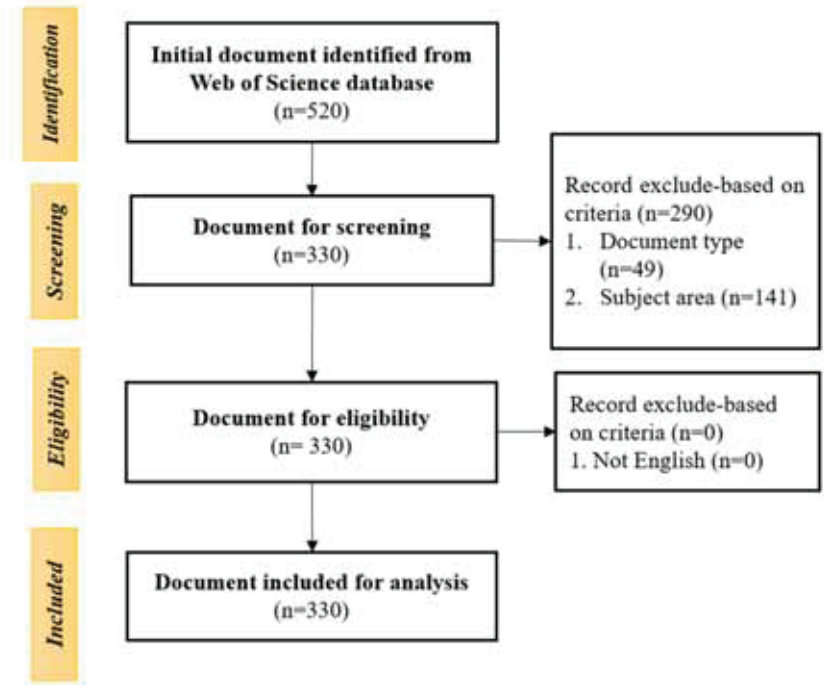

Fig. 1: PRISMA flow diagram of the study selection process

Table 2: Bibliometric parameters

Category	Parameter	Description
Productivity	Number of publications per year	Measuring the trends of research growth over time.
	Number of articles per author/institution/country	Identifying the most productive actors in the field of green behavior and sustainability education.
Impact	Number of citations per article	Measuring the influence or relevance of articles in the scientific community.
	Most productive journal	Identifying which journals publish the most articles about the topic.
	Impact factor (IF)	Assessing the reputation of journals using citation-based impact scores.
Collaboration	Collaboration between countries	Analyzing international research collaboration in the field.
Content	Keyword co-occurrence	Identifying key terms that frequently appear together to determine major themes.
	Clustering and trending topics	Exploring topic clusters and how they evolve over time.

Data analysis

It is exported plain text from the Web of Science database for bibliometric analysis. Citespace and Biblioshiny were the primary tools used in this study. The performance metrics were evaluated using Biblioshiny, focusing on publication output, the most cited sources and authors, key documents, and thematic relevance. Biblioshiny and CiteSpace are effective in mapping knowledge structures by producing reliable co-occurrence networks and thematic clusters (Aria and Cuccurullo, 2017; Chen, 2017). Nonetheless, the precision of their results relies on the quality of metadata, the configuration of parameters, and the versions of the software, all of which can influence visualization and reproducibility (van Eck and Waltman, 2014). To address these limitations, this study documented search parameters and cross-validated results across both tools to ensure transparency and reliability.

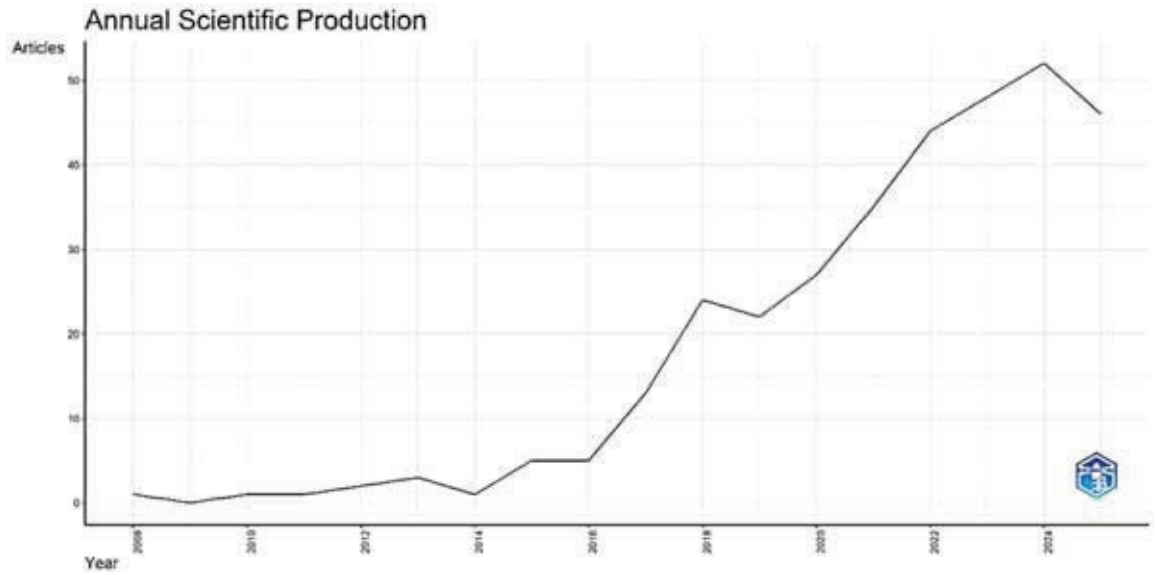

Fig. 2: Annual growth of publications on green behavior in education (2008–2025)

Narrative synthesis of influential studies

This study not only utilized bibliometric mapping but also integrated a narrative synthesis of significant publications to broader insight into the field. While bibliometric techniques are effective for identifying trends, networks, and clusters, they are limited in explaining how individual studies contribute to theory, methodology, and practice (Snyder, 2019; Xiao and Watson, 2019). To mitigate this limitation, the narrative synthesis concentrated on the top 20 most-cited and thematically relevant papers. Each article was read in depth and analyzed according to its methodology, main findings, and contributions to the field. This method enhances the quantitative mapping by elucidating how foundational works have influenced conceptual frameworks, progressed methodological approaches, and informed educational and institutional practices.

Emerging bibliometric tools and future opportunities

Emerging bibliometric and network analysis tools increasingly improve cross-disciplinary synthesis by integrating data from multiple fields. Artificial intelligence and machine learning facilitate automated text mining and topic modeling, which help to uncover concealed relationships across the fields of environmental science, management, and education (Donthu *et al.,* 2021). At the same time, advances in interoperability and open-access platforms allow more efficient database integration, while user-friendly visualization dashboards make bibliometric mapping accessible beyond specialists (Cobo *et al.,* 2011). Combined with automation, these innovations enhance reproducibility and suggest a shift from static mapping toward dynamic, real-time knowledge systems.

RESULT AND DISCUSSION

Bibliometric analysist

Bibliometric analysis shows rapid growth of research on green behavior in education between 2008 and 2025, with an annual increase of 25.26 percent and 330 publications across 111 journals. The discipline includes 1,076 authors, with an average of 3.47 authors per paper, while works by a single author are infrequent (25), reflecting significant collaboration. International co-authorship accounts for 31.52 percent of documents. With 18,625 references, 1,149 keywords, and an average citation rate of 19 per article, this literature is both robust and influential. The standard document age stands at 3.55 years, highlighting its importance in modern sustainability discussions.

Fig. 2 illustrates that studies on environmentally friendly behavior in education were scarce from 2008 to 2015, averaging less than ten publications

annually. Output rose sharply after 2016, recording an average annual growth rate of 25.26 percent and reaching its peak in 2023. This increase signifies a heightened worldwide awareness of climate change, the assimilation of sustainability into teaching materials, and supportive policy initiatives including the sustainable development goals (SDGs) and the Paris Agreement (UNESCO, 2017; IPCC, 2018). The expansion is concentrated in advanced economies, particularly the United States, China, and the United Kingdom, while contributions from Latin America and Africa remain modest due to persistent barriers in funding and research capacity (Tilbury, 2011; Leal Filho *et al.,* 2016, 2020). Maintaining this path will necessitate inclusive funding, institutional capacity building, and open-access knowledge platforms, as well as interdisciplinary collaboration that integrates education, psychology, management, and environmental sciences (Hallinger and Chatpinyakoop, 2019; Yang *et al.,* 2023; You *et al.,* 2024).

Country collaboration

Fig. 3 illustrates that research on green behavior in education follows a clear core–periphery pattern. The United States, China, the United Kingdom, Germany, Australia, and Malaysia serve as central hubs, supported by strong funding and established academic networks (Tijssen *et al.,* 2012; Waltman *et al.,* 2011). Collaboration is particularly strong among English-speaking countries, while regions such as the Middle East and Latin America remain at the periphery due to limited resources and institutional capacity (North *et al.,* 2020). Recent studies utilizing Scopus data affirm the persistent supremacy of the United States and highlight the uneven contributions from developing regions (You *et al.,* 2024; Yang *et al.,* 2023). Addressing these disparities requires inclusive funding mechanisms, capacity-building initiatives, and stronger North–South and South–South partnerships, supported by regional hubs and open-access platforms, to foster a more balanced and integrated research landscape.

Table 3 shows that the United States leads the field with the highest citations (56) and centrality score (0.32), followed by China, Germany, Malaysia, Australia, and the United Kingdom. Malaysia emerges



Fig. 3: International collaboration network on green behavior in education

Table 3: State productivity

No.	Countries	Year	Rank	Centrality	TC
1	USA	2012	1	0.32	56
2	China	2018	2	0.08	36
3	Germany	2011	3	0.09	27
4	Malaysia	2016	4	0.23	26
5	Australia	2013	5	0.32	23
6	England	2016	6	0.32	21
7	Taiwan	2017	7	0.02	17
8	Canada	2018	8	0.02	16
9	Pakistan	2019	9	0.19	12
10	Spain	2018	10	0.01	11
11	Italy	2016	11	0.05	10
12	Austria	2017	12	0.05	10
13	Saudi Arabia	2021	13	0.01	9
14	Israel	2013	14	0.01	8
15	Finland	2015	15	0.01	8
16	Brazil	2013	16	0.01	8
17	India	2020	17	0.03	8
18	Lithuania	2020	18	0.03	8
19	Indonesia	2019	19	0.01	8
20	Iran	2016	20	0.02	7

Table 4: Source reputation

Rank	Source	Region	TC	Quartile
1	Journal of Cleaner Production	Netherlands	997	Q1
2	Journal of Environmental Psychology	Netherlands	895	Q1
3	Sustainability (Basel)	Switzerland	782	Q2
4	Environmental Education Research	UK	560	Q1
5	Environment and Behavior	USA	433	Q1
6	International Journal of Sustainability in Higher Education	UK	300	Q1
7	Journal of Environmental Education	USA	264	Q1
8	Global Environmental Change	UK	250	Q1
9	Ecological Economics	Netherlands	174	Q1
10	Journal of Social Issues	USA	154	Q1
11	Journal of Business Ethics	Netherlands	148	Q1
12	Energy Policy	UK	118	Q1
13	Frontiers in Psychology	Switzerland	108	Q2
14	Resources, Conservation and Recycling	Netherlands	103	Q1
15	International Journal of Environmental Research and Public Health	Switzerland	98	Q2
16	Journal of Business Research	USA	92	Q1
17	Business Strategy and the Environment	UK	88	Q1
18	Nature Climate Change	UK	84	Q1
19	Journal of Environmental Management	UK	81	Q1
20	Global Journal of Environmental Science and Management	USA	33	Q1

as a key hub in Southeast Asia, while Pakistan and Indonesia have increased their participation since 2019. Conversely, Bangladesh, Hungary, and much of Latin America and Africa face underrepresentation stemming from systemic barriers and limited resources (North *et al.,* 2020; Pedraja-Rejas *et al.,* 2023). Addressing these gaps requires targeted funding, institutional support, and more inclusive North–South and South–South collaborations, with regional hubs and academic diplomacy helping to reduce disparities and promote equitable policy outcomes (Cortés *et al.,* 2021).

The most influental Journal

Table 4 shows that the Journal of Cleaner Production is the leading outlet in green behavior

Table 5: Most influential author

Rank	Author	Documents (NP)	Total citations (TC)
1	Zwickle, A.	2	217
2	Yu, T.-Y.	5	158
3	Yu, Tai-Kuei	4	157
4	Greenland, S.	3	150
5	Chao, C.-M.	2	126
6	Brown, Martin	2	112
7	Naboni, E.	2	112
8	Sonetti, G.	2	112
9	Lobo, A.	2	104
10	Tolppanen, S.	5	88
11	Monus, F.	3	68
12	Brock, A.	3	64
13	Grund, J.	3	64
14	Kang, J.	3	63
15	Pickering, G.J.	3	57
16	Sidiropoulos, E.	2	53
17	Bogner, F.X.	2	52
18	Garcia-Machado, J.J.	2	51
19	Zhao, J.	2	46
20	Tayne, K.	2	42
21	Saif, N.	1	18
22	Sulphey, M.M.	2	11
23	Adow, A.H.E.	1	11
24	Alkahtani, N.S.	1	11
25	Senan, N.A.M.	1	11
26	Rama, A.S.	1	2
27	Susanto, P.	1	2
28	Mardianti, F.	1	2
29	Purba, D.E.	1	2

research with 997 citations, followed by the Journal of Environmental Psychology (895) and *Sustainability-Basel* (782). These journals, most of which are Q1-ranked and published in developed countries, underline the strong scientific influence and international visibility of the field. Their preeminence further demonstrates the interdisciplinary character of this research domain, positioned at the interface of education, psychology, and management.

The most of influental authors

Table 5 highlights influential authors such as Zwickle, Yu Tai-Yi, and Yu Tai-Kuei, whose work has significantly shaped the field. Their citation records reflect both productivity and sustained international collaboration across Asia, Europe, and North America. The combination of established academics and budding researchers demonstrates the enhancement of research capabilities and the broadening of perspectives. This indicates that the field has transitioned from focusing on individual efforts to fostering a more cohesive global research network.

Table 6 shows that the most cited documents reflect important thematic shifts. Early studies, such as Ojala (2012), emphasized environmental attitudes and emotions, while later works, including Ritter *et al.,* (2015), Hou *et al.,* (2020), and Faraz *et al.*,(2021), broadened the focus to consumer behavior, sustainable management, and leadership. The escalating citation impact of these studies reveals that the research on green behavior in education has become more influential and significant policy and institutional practice. Over the years, the discipline has transitioned from descriptive research to more practical, solution-driven methodologies, incorporating insights from education, psychology, organizational studies, and environmental management. Recent directions highlight digital tools, sustainable consumption, and leadership frameworks that link institutions with broader sustainability goals.

Most frequently discussed themes

Fig. 3 illustrates that the bibliometric visualization

Table 6: The most influential articles

Author (year)	Region	Source	Total citations	TC per Year
Ojala, 2012	Sweden	Environmental Education Research	516	33.29
Ritter *et al.*, 2015	USA	Journal of Cleaner Production	226	20.55
Hou *et al.*, 2020	China	Science of the Total Environment	179	29.83
Faraz *et al.*, 2021	Pakistan	Corporate Social Responsibility and Environmental Management	149	29.80
Wamsler *et al.*, 2018	Germany	Sustainability Science	149	18.63
Whitley *et al.*, 2018	USA	Environmental Education Research	128	16.00
Meyer, 2016	Germany	Journal of Cleaner Production	104	11.56
Al-Naqbi and Alshannag, 2018	UAE	Int J Sustain Higher Educ	96	12.00
Sonetti *et al.*, 2019	Italy	Sustainability	91	18.20
Yu *et al.*, 2017	Hong Kong	Journal of Cleaner Production	91	13.00
Heeren *et al.*, 2016	Netherlands	International Journal of Sustainability in Higher Educattion	88	9.78
Zhang *et al.*, 2019	China	Sustainability	88	17.60
Sun *et al.*, 2018	China	Business Strategy and the Environment	85	10.63
Wynveen *et al.*, 2015	USA	Coastal Management	72	6.55
Baker *et al.*, 2021	USA	Environmental Education Research	71	35.50
Nguyen *et al.*, 2017	Vietnam	Asia Pacific Journal of Marketing Logistic	71	10.14
Bofferding and Kloser, 2015	USA	Environmental Education Research	69	6.27
Lazaric *et al.*, 2020	France	Journal of Evolutionary Economics	67	16.75
Scurati *et al.*, 2021	Italy	Sustainability (Basel)	67	33.50
Schelly *et al.*, 2012	USA	Journal of Environmental Education	67	4.79
Saif *et al.*, 2023	USA	Global Journal of Environmental Science and Management	18	9.0
Sulphey *et al.*, 2024	USA	Global Journal of Environmental Science and Management	8	8.0
Mardianti and Purba, 2023	USA	Global Journal of Environmental Science and Management	2	1.0

highlights ten key clusters in green behavior and education research (Q = 0.4124; S = 0.6629), reflecting a substantial and consistent framework. To provide greater clarity, these clusters are synthesized in Table 7, which maps them into three higher-order dimensions: individual factors, organizational drivers, and systemic conditions.

Thematic clusters and conceptual structures

The bibliometric analysis identifies ten clusters grouped into three dimensions: individual factors (attitudes, norms, intentions), organizational drivers (Green HRM, OCBE, transformational leadership), and systemic conditions (policy frameworks, sustainable consumption, Global South contexts). Leadership aligns personal motivations with organizational practices, where GHRM enhancing skills, OCBE promotes voluntary initiatives, and leadership influences cultures focused on sustainability. At the individual level, TPB and VBN explain how attitudes and norms drive intentions, supported by interventions such as campaigns, gamification, and experiential learning. Systemically, green marketing and education promote sustainable consumption through literacy and policies. Over time, research has shifted from individual behavior to organizational and systemic governance, with best practices like student initiatives, green procurement, and campus-community living labs. Nonetheless, there are persistent gaps in cross-national comparisons, involvement from the Global South, and advancements in digital innovation that require attention to ensure ESD is more closely aligned with leadership, HRM, and sustainability objectives.

Trending topic

Fig. 5 shows the development of keyword usage in research on environmentally friendly behavior over the past decade. Since 2021, there has been a notable increase in the emphasis on pro-environmental

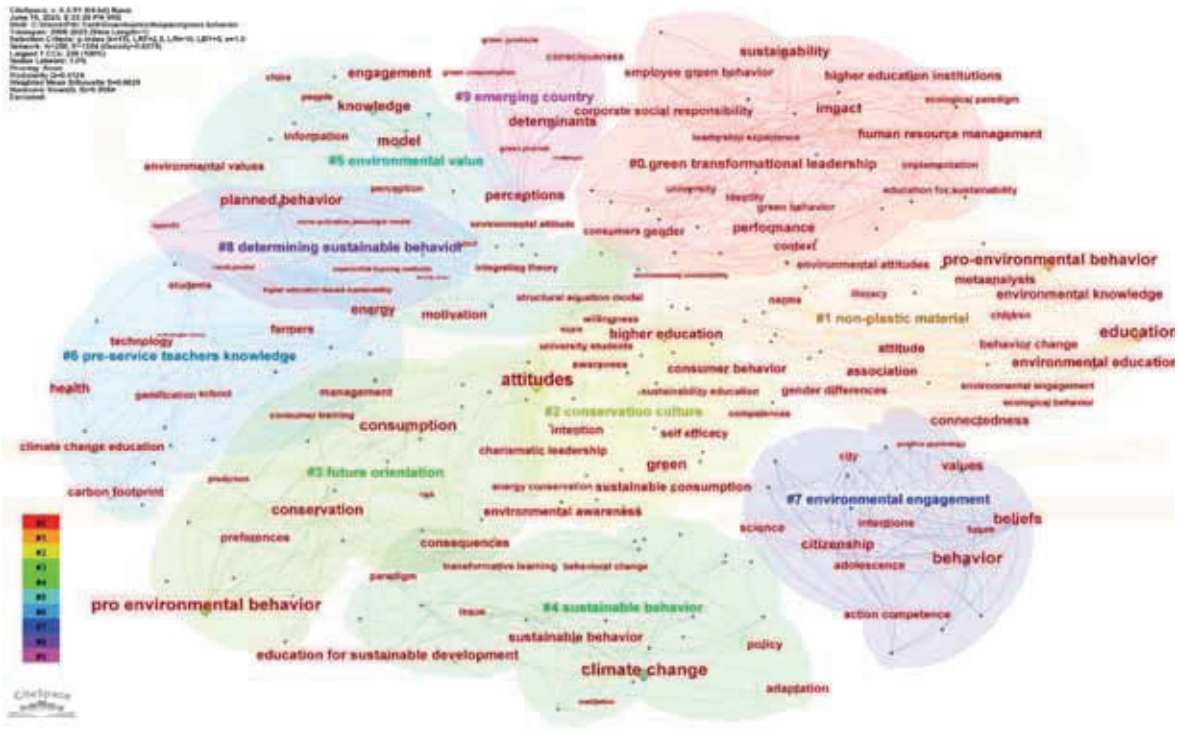

Fig. 4: Research themes in green behavior through education

Table 7: Thematic cluster

Dimension	Cluster	Key themes (Keywords)	Synthesis
Individual factors	1 (Orange)	Attitudes, behavior change, environmental knowledge	Attitudes, values, norms, and knowledge shape behavioral intentions. Explained by TPB and value-belief-norm theory (VBN); supported by literacy, campaigns, gamification, and experiential learning.
	2 (Lime yellow)	Sustainable consumption, consumer behavior, conservation culture	
	3 (Light green)	Risk, consequences, future orientation	
	5 (Turquoise green)	Engagement, motivation, environmental values	
	8 (Dark purple)	Planned behavior, attitudes, norms, energy use	
Organizational drivers	0 (Red)	Leadership, CSR, higher education, identity	Organizational drivers foster competencies, voluntary pro-environmental action, and sustainability-oriented cultures through HRM, OCBE, and leadership practices.
	4 (Bluish green)	Sustainable behavior, ESD, transformative learning, climate change	
	6 (Light blue)	Climate education, technology, teacher training, gamification	
	7 (Dark blue)	Citizenship, beliefs, values, action competence	
Systemic conditions	9 (Pink)	Perceptions, determinants, community-based education in developing countries	Systemic conditions emphasize inclusive policies and community-based education to address socio-ecological challenges in emerging contexts.

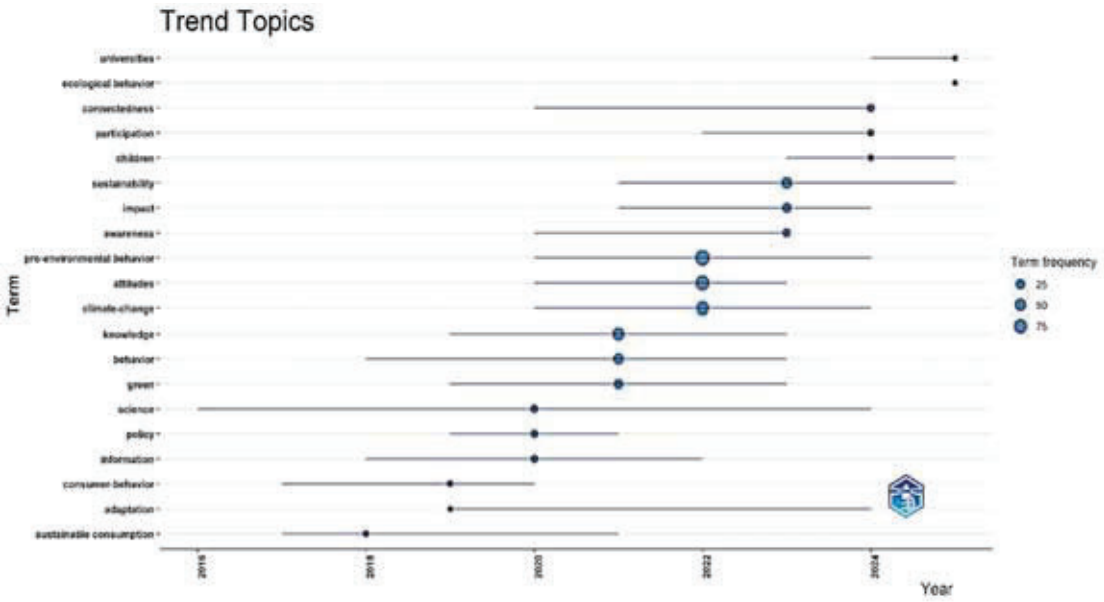

Fig. 5: Trending research topics in green behavior and education (2013–2024)

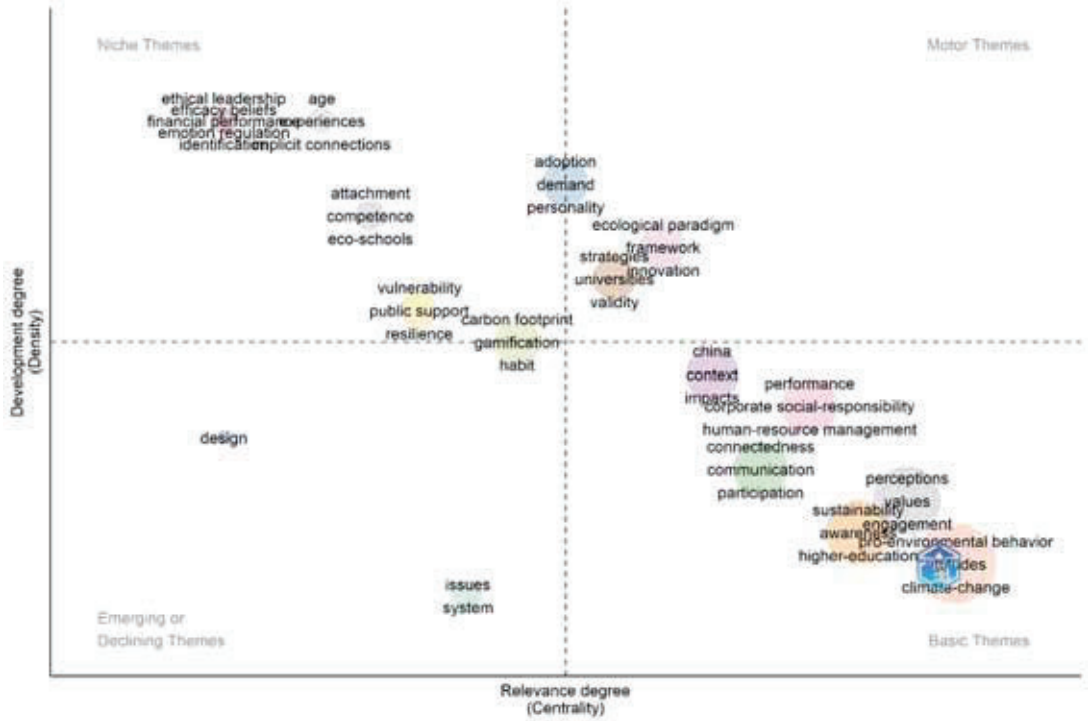

Fig. 6: Thematic map of green behavior research in education

behaviors, attitudes, awareness of climate change, and engagement, showcasing a movement towards psychological and social dimensions. In 2023–2024, terms such as sustainability and impact emerged, signaling a new focus on practical applications, especially in higher education. Topics like ecological

behavior and interconnectedness have also come to light, bolstering the research trajectory aimed at human-environment relationships.

Fig. 6 illustrates the distribution of themes by their growth and relevance. Core topics such as universities, innovation, strategy, and ecological paradigms emerge as rapidly developing areas, while sustainability, climate change, and environmental awareness remain stable foundations. Ethical leadership and financial performance appear as niche themes, whereas design and systems are positioned as emerging or declining. The map illustrates the rising use and cross-disciplinary nature of green behavior research in educational contexts.

Narrative Synthesis of Influential Studies

Moreover, a detailed analysis of influential studies is required in addition to bibliometric mapping to better understand their effects on research concerning green behavior and sustainable development education. While bibliometric indicators reveal trends and clusters, they cannot fully explain conceptual and empirical contributions. To bridge this gap, Table 8 presents a synthesis of twenty-three highly cited publications, highlighting their methods, findings, and key contributions. This narrative review enhances the quantitative analysis by elucidating the intellectual foundations and research trajectories within the field.

Key studies highlight diverse drivers of green behavior. Ojala (2012) showed hope as a motivator, while Whitley (2018) and Wynveen (2015) confirmed the role of VBN theory. Ritter (2015), Nguyen (2017), and Lazaric (2020) linked attitudes, altruism, and social influence to sustainable consumption, extending insights to the global south. Hou (2020) stressed cross-disciplinary soil management, and Wamsler (2018) integrated mindfulness into ESD. Leadership emerged as central. Faraz (2021) and Saif (2023) demonstrated how servant and transformational leadership foster pro-environmental actions, while Zhang (2019) tied HRM to eco-innovation. Studies in higher education Meyer (2016); Al-Naqbi (2018) and Sonetti (2019) emphasized knowledge, institutional culture, and whole-institution approaches, though Heeren (2016) showed knowledge alone is insufficient. Practical innovations include VR for behavior change (Scurati 2021), green product perceptions (Sun 2018; Yu 2017), and conservation culture at schools (Schelly 2012; Bofferding 2015). Broader reviews (Sulphey 2024; ; Wals and Benavot, 2017; Barth and Rieckmann, 2016) and case studies (Mardianti and Purba 2023) highlight organizational citizenship behavior and socio-economic influences on civic participation. Collectively, these studies uncover the psychological, organizational, and systemic elements that influence green behavior in various contexts. This study combines bibliometric mapping with narrative synthesis to provide a comprehensive understanding of how education fosters green behavior. The thematic clusters revealed in the analysis underscore three primary dimensions: individual, organizational, and systemic, which together provide a conceptual and practical framework for the field. At the individual level, attitudes, values, and emotions such as hope, mindfulness, and resilience strongly influence engagement. These findings are consistent with the theory of planned behavior (TPB) (Ajzen, 1991) and the value–belief–norm model (Stern, 2000), which explain how attitudes, perceived norms, and moral obligations shape behavioral intentions. Evidence from narratives demonstrates that possessing knowledge by itself does not lead to changes in behavior (Heeren *et al.,* 2016). More effective approaches include norm-based campaigns, experiential learning, and gamification (Lampropoulos and Kinshuk, 2024; Mabalay, 2024). Research in schools highlights the importance of early climate literacy (Bofferding and Kloser, 2015; Schelly *et al.,* 2012), while studies in higher education emphasize leadership and governance (Sonetti *et al.,* 2019; Lozano *et al.,* 2021). Organizational factors significantly influence sustainability results. Practices such as green human resource management, organizational citizenship behavior for the environment, and sustainability-oriented leadership foster institutional cultures that support pro-environmental action (Faraz *et al.,* 2021; Zhang *et al.,* 2019; Sulphey *et al.,* 2024). Transformational leadership enhances creativity and intrinsic motivation, in contrast to the more indirect effects of transactional leadership (Saif *et al.,* 2023). Universities reinforce these drivers through curriculum reform, sustainability-oriented recruitment, and governance strategies that align institutional missions with the Sustainable Development Goals (Lozano *et al.,* 2015; Gregori-Giralt *et al.,* 2025; Finatto *et al.,* 2024; Ataya, 2018). Student-driven projects, living labs on campus, and sustainable purchasing practices

Table 8: Narrative Synthesis

Author (Year)	Main findings	Contribution
Ojala, 2012	Hope is a key predictor of environmental engagement among young people	Introduced psychological and emotional dimensions into environmental behavior research
Ritter *et al.,* 2015	Positive attitudes and intrinsic motivation drive green product consumption	Provided Global South perspective on green consumer behavior
Hou *et al.,* 2020	Sustainable soil management requires cross-disciplinary approaches	Linked environmental management issues with sustainability education
Faraz *et al.,* 2021	Green servant leadership fosters self-efficacy toward pro-environmental behavior	Connected green leadership with organizational psychology
Wamsler *et al.,* 2018	Mindfulness practices enhance sustainability awareness and behavior	Expanded ESD into spiritual and psychological domains
Whitley *et al.,* 2018	Values and norms strongly shape sustainable student behaviors	Validated VBN theory in higher education settings
Meyer, 2016	Demographics and years on campus affect pro-environmental behavior	Showed heterogeneity of green behavior in higher education
Al-Naqbi and Alshannag, 2018	Knowledge influences attitudes, which shape sustainable behaviors	Contextualized ESD in Gulf countries
Sonetti *et al.,* 2019	HEIs as triggers of regenerative sustainability	Promoted whole-institution approach in higher education
Yu *et al.,* 2017	Attitudes and peer pressure affect green product purchase intention	Validated TPB in East Asian educational context
Heeren *et al.,* 2016	Knowledge alone is insufficient for behavior change	Highlighted non-cognitive factors in ESD
Zhang *et al.,* 2019	Green HRM promotes green behavior through eco-innovation acceptance	Integrated human resource management (HRM) with technology adoption models
Sun *et al.,* 2018	Environmental knowledge and product quality affect attitudes toward green products	Linked education, product perception, and green manufacturing
Wynveen *et al.,* 2015	VBN explains pro-environmental behavior in marine settings	Extended VBN theory to ecological domains
Baker *et al.,* 2021	Children's emotional resilience is critical in climate education	Connected resilience, emotions, and environmental education
Nguyen *et al.,* 2017	Altruistic values drive purchase of energy-efficient appliances	Provided Southeast Asian evidence for green consumerism
Bofferding and Kloser, 2015	Students show limited understanding of climate mitigation/adaptation	Identified gaps in climate literacy at early education levels
Lazaric *et al.,* 2020	Social influence and values shape sustainable consumption	Reinforced role of social norms in Europe
Scurati *et al.,* 2021	Virtual reality supports sustainable behavioral change	Introduced emerging technologies in ESD
Schelly *et al.,* 2012	Conservation culture can be built through education and modeling	Demonstrated practical school-level environmental citizenship
Saif *et al.,* 2023	Transformational leadership strongly boosts green creativity via intrinsic motivation; transactional leadership only affects motivation	Introduces green transactional leadership; shows leadership styles shape student creativity for sustainability
Sulphey *et al.,* 2024	OCB-E research (eco-initiative, civic engagement, helping) has surged; improves organizational green performance	First bibliometric synthesis of OCB-E; underscores voluntary behavior for corporate greening
Mardianti and Purba, 2023	Participation in water management shaped by socioeconomics; income/education reduce, women/unmarried increase participation	Shows socioeconomics can hinder or enable pro-environmental action; informs urban water policy

illustrate the implementation of sustainability in real-world scenarios. Systemic factors enhance personal and organizational behaviors by integrating sustainability within extensive societal contexts. Consumer education and sustainable marketing encourage responsible consumption (Peattie and Crane, 2005; Gadenne *et al.,* 2009), while community-based initiatives in developing countries demonstrate how socio-economic factors shape environmental participation (Mardianti and Purba, 2023). These conclusions emphasize the importance of having policies that are both inclusive and context-sensitive. Bibliometric evidence confirms these differences: advanced economies often emphasize psychological drivers (Whitley *et al.,* 2018), whereas emerging economies focus on governance and institutional capacity (Nguyen *et al.,* 2017; Yu *et al.,* 2017). Global patterns highlight both progress and persistent disparities. Research on green behavior has expanded rapidly since 2016, led by the United States, China, Malaysia, and the United Kingdom. Despite this, collaboration networks show significant unevenness, with a core–periphery structure that is largely controlled by English-speaking countries, while Latin America, Africa, and the Middle East are still underrepresented (North *et al.,* 2020; Leal Filho *et al.,* 2018; Cerdeira *et al.,* 2023). The limited partnerships between North and South, as well as South and South, hinder knowledge exchange and innovation, highlighting the necessity for focused funding, effective leadership, and capacity enhancement (Tijssen *et al.,* 2012; Cortes *et al.,* 2021). Conceptually, the field has shifted from a narrow focus on individual psychology to a broader emphasis on organizational practices and governance, reflecting sustainability as both a behavioral and structural challenge (Tilbury, 2011; Liobikiene and Bernatoniene, 2017; Romulo *et al.,* 2024). Despite these advancements, considerable gaps still exist. Comparative studies across countries are few, contributions from the Global South are restricted, and digital innovations such as gamification, online learning, and virtual reality remain underused (Scurati *et al.,* 2021; Radianti *et al.,* 2020; Alyoussef, 2021). Theoretical perspectives also remain fragmented. Models such as the TPB, the value–belief–norm model, and the technology acceptance model (Davis, 1989; Si *et al*., 2019; Ajina *et al.,* 2024; Tian and Liu, 2022; Voulvoulis *et al.,* 2022) continue to guide research, but integrative frameworks that link behavioral, organizational, and systemic perspectives are still lacking. Narrative studies underscores the necessity of addressing these divides through the development of models that are sensitive to context and relevant on a global scale (Hallinger and Chatpinyakoop, 2019). Expanding interdisciplinary collaboration and strengthening South–South networks will be essential to improve inclusivity and accelerate the role of education in achieving sustainable development (Leal Filho *et al.,* 2020; Bowser *et al.,* 2024; Fredman, 2023).

CONCLUSION

This study illustrates that the investigation of environmentally friendly behavior in education has emerged as a notably significant field of study, experiencing substantial increase in scholarly contributions since 2016. While developed nations continue to dominate contributions, the active engagement of developing countries is gradually expanding, reflecting the global relevance of this field. The findings confirm that education is not merely a channel for knowledge dissemination but a strategic driver of environmental transformation, fostering pro-environmental values, behaviors, and institutional practices that advance sustainability. In particular, higher education institutions act as transformative spaces for the systematic incorporation of sustainability principles into curricula, organizational culture, and campus operations—including waste management, energy efficiency, and green governance. By presenting the first global bibliometric mapping of green behavior and education for sustainable development up to 2025, this study offers novel insights into authorship patterns, collaboration networks, and thematic clusters, providing an evidence-based foundation for strengthening environmental management and sustainability governance worldwide. The findings of the study carry important consequences for the management of the environment and the formulation of policies. Initially, the bibliometric mapping reveals that education-focused green behavior is not only an academic issue but also a strategic instrument for attaining sustainable governance. Governments can use these insights to develop policies that include education for sustainable development into national curricula and environmental programs, thereby expanding universities' and schools' responsibilities as agents of

behavioral change. Second, the results emphasize the significance of adopting whole-institution strategies in higher education, which consist of systematically embedding environmental management policies into teaching, research, and campus operations. The study emphasizes the importance of incorporating governance measures focused on sustainability, including waste management systems, carbon footprint reduction, and energy efficiency programs, to transform campuses into sustainable living laboratories. Third, the identification of clusters such as transformational leadership, conservation culture, and green human resource management suggests that businesses incorporate pro-environmental ideas into leadership training, HR policy, and institutional planning. To improve these behaviors, policymakers could incentivize sustainable business practices, while managers have the opportunity to establish reward systems and communication strategies that foster ecological citizenship among both employees and students. Finally, the worldwide imbalances demonstrated by collaboration networks highlight the significance of improving international cooperation, particularly in supporting developing countries with sustainability research. Academic diplomacy, cross-country funding, and international networks can all contribute to bring underrepresented regions into global environmental governance frameworks. By addressing these gaps, stakeholders can ensure that green behavior are inclusive, fair, and scalable across various environments. This study has several limitations that should be acknowledged. First, the analysis was restricted to articles indexed in the Web of Science and published in English, which may have excluded valuable insights from local or non-English sources. Second, the bibliometric approach provides primarily a quantitative overview and therefore does not capture in depth the contextual and qualitative aspects of the literature. Future research should address these limitations by expanding the scope of databases to include Scopus, Google Scholar, and regional indexes in order to present a more comprehensive global picture. Furthermore, integrating bibliometric analysis with systematic qualitative reviews would allow researchers to evaluate thematic depth, methodological strategies, and contextual case studies more efficiently. Empirical studies are also needed to evaluate the effectiveness of educational interventions—such as gamification, digital learning platforms, and eco-spirituality approaches—in shaping sustainable behavior. Moreover, comparative studies across different countries could provide insights into how cultural, institutional, and policy frameworks impact the effectiveness of integrating green practices into educational systems. Finally, greater attention should be given to cross-sectoral collaborations between academia, industry, and government in order to design integrative sustainability policies and operationalize green behavior into actionable strategies for environmental management.

AUTHOR CONTRIBUTIONS

P. Yanti led the conception and design of the study, developed the research framework, and coordinated the overall manuscript preparation. V. Gaffar supervised the research process, provided critical guidance on theoretical positioning, and contributed to the refinement of arguments and interpretation of findings. P. Harisandi was responsible for data collection, bibliometric analysis, and visualization using Biblioshiny and CiteSpace. I. Ramadhani supported the systematic literature screening process, contributed to drafting the methods and results sections, and assisted in data interpretation. T. Yuliawati contributed to the review of related literature, analysis of thematic clusters, and manuscript editing for coherence and clarity. S. Yusriani provided input on international collaboration perspectives, contextualized the findings within sustainability governance, and reviewed the final version of the manuscript. All authors read and approved the final manuscript.

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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.

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ABBREVIATIONS

%	Percent
APJML	Asia Pacific Journal of Marketing and Logistics
BPI	Beasiswa Pendidikan Indonesia
CSR	Corporate social responsibility
DOI	Digital object identifier
ECSR	Environmental citizenship for sustainable resource use
ESD	Education for sustainable development
EU	European Union
GHRM	Green human resource management
GJESM	Global Journal of Environmental Science and Management
IF	Impact factor
NP	Number of Publications
OCBE	Organizational Citizenship Behavior for the Environment
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
Q1/Q2	Quartile ranking of academic journals (Scimago/Clarivate)
SCI	Science Citation Index
SDGs	Sustainable development goals
SJR	SCImago Journal Rank
SSCI	Social Sciences Citation Index
TC	Total citations
TPB	Theory of planned behavior
UAE	United Arab Emirates
UK	United Kingdom
USA	United States of America
VBN	Value-belief-norm theory
WoS	Web of Science

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REVIEW PAPER

Bio-ecological characteristics of invasive foliar nematode *Aphelenchoides fragariae* and its safe and effective management

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ABSTRACT

Aphelenchoides fragariae, the foliar nematode, is an emerging phytosanitary threat in Indonesia, attacking horticulturals. Initially documented on Andrographis paniculata in 2003, it has now extended to strawberry, shallot, garlic, dracaena, and several ferns. The humid tropical climate of Indonesia, along with its frequent rain, promotes its survival and expansion. This study documents its incidence and quarantine records, summarizes knowledge of biology, host range, and transmission, assesses environmentally safe control measures, and recommends integrated pest management strategies for sustainable horticulturals. This study aimed to encapsulate the *Aphelenchoides fragariae* species as an invasive species, examining its influence on horticultural systems and the approaches for its management. The study synthesizes national and international literature through the year 2025 to consolidate knowledge on the biology, host range, transmission pathways, documented damage, diagnostic methods, and management options for *Aphelenchoides fragariae* relevant to Indonesian horticulture. The elements affecting production and trade, as well as eco-friendly control alternatives, were investigated and pinpointed to recommend a practical integrated pest management system that bolsters national agricultural progress and adheres to global phytosanitary requirements. *Aphelenchoides fragariae* persists in plant debris, enters dormancy under stress, and reproduces rapidly, with a host range of nearly five hundred species across one hundred families. It spreads through rain splash, sprinkler irrigation, infected foliage, asymptomatic planting material, and trade. The nematode causes severe defoliation reported as 60–80 percent and 65–82 percent yield decline under heavy infestation. Alternative management strategies must align with integrated pest management principles, focusing on prevention and low-impact solutions. Use of pest-free planting material, quarantine, molecular surveillance, residue removal, drip irrigation are preventing infestations, hot water treatment, validated botanical nematicides (neem, cashew nutshell liquid, essential oils), biological antagonists, and regulated use of low-toxicity chemicals only as a last resort are suppressing populations. Environmentally safe management of nematodes relies on biological measures such as botanicals, beneficial and antagonistic microbes. Techniques including hot water treatment and sanitation contribute to the reduction of inoculum. Limited use of low-toxicity chemicals, quarantine safeguards, and regulation further improve environmental safety. To achieve effective implementation, it is essential to provide training for farmers, ensure thorough monitoring, foster collaboration, and integrate nematode surveillance within early warning systems.

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INTRODUCTION

The foliar nematode *Aphelenchoides fragariae* (Aphelenchida: Aphelenchoididae) is a significant pest to horticultural crops (Lopes-Caitar *et al.,* 2019). It affects a wide range of agricultural plants, including ferns, ornamental foliage, flowering plants, and both herbaceous and woody perennials (Kohl, 2011). Regarded as a global quarantine pest, this nematode—commonly called the bud and leaf nematode, fern nematode, or strawberry crimp nematode—is known for its invasive behavior and damaging capabilities (CABI, 2022). By infecting the aerial parts of plants, *A. fragariae* can severely impact the health and marketability of crops in nurseries, greenhouses, and landscapes (Jagdale and Grewal, 2006). It causes visible damage such as leaf necrosis and interveinal chlorosis, which degrade plant appearance and reduce ornamental value (Sánchez Monge *et al*., 2015). The nematode infiltrates the leaves either by penetrating the epidermis directly or through the stomata, utilizing a stylet for intercellular feeding, causing cell death and discoloration (Desaeger and Noling, 2017). Eggs are deposited in mesophyll tissue, parenchyma, or buds, further aggravating the damage (Klingler, 1970; Riedel and Larsen, 1974). The economic consequences of *A. fragariae* are substantial, particularly in ornamental nurseries, where infestations have led to revenue losses in the millions of dollars annually (Howland and Quintanilla 2023; Jagdale and Grewal, 2002). For instance, in the United States, the nursery industry is experiencing heightened risks from foliar nematodes because of the increasing interstate and international plant trade (USDA, 2007; McCuiston *et al*., 2007). The global ornamental industry, estimated to be worth around United States dollars (USD) 70 billion (Madhavan *et al.*, 2021), is increasingly concerned about the unintentional transport of *A. fragariae*. Parts of plants that are infested, along with the associated growing media, often act as common carriers of this pest in trade (EPPO, 2022; CABI, 2022). Regulatory measures to prevent its spread have been adopted in at least 47 countries (Lehman, 2004), with current data suggesting that even more nations have introduced quarantine rules in recent years (CABI, 2022; EPPO, 2022). Aphelenchoides is recognized as one of the most often detected nematode genera across the globe, emphasizing its considerable potential for distribution through global commerce (Mani, 1998). In Indonesia, increased occurrences of foliar nematode outbreaks have recently been reported. Understanding the host range, survival, and reproduction of *A. fragariae* is vital for risk assessment and quarantine measures. Effective management should encompass bioecology, infection routes, natural enemies, resistant plant species, and chemical or botanical interventions, along with the use of healthy planting material. Cultural, physical, and chemical methods have also shown promise in suppressing its populations. Microbial biocontrol agents and plant-derived biochemicals have proven to possess nematicidal properties in systems involving ornamental crops (Djiwanti and Supriadi, 2011; An *et al*., 2017; Promsai *et al.,* 2023; Srikanth *et al.,* 2023). Furthermore, newer, safer-generation chemical treatments have proven effective under both nursery and field conditions. This review assesses the current status of *A. fragariae* as a threat to the Indonesian horticulture industry, examines its potential economic impact, and summarizes sustainable, effective control methods. Furthermore, forthcoming views on a well-rounded and sustainable management strategy are discussed. Synthesization and characterization of the *A. fragariae* species and its impact on horticultural systems, and its management were discussed. Recommendation for eco-friendly control strategies that correspond with national agricultural development aims and global phytosanitary regulations were presented. The aims of this study are to synthesize and characterize of the *Aphelenchoides fragariae* species and its impact on horticultural systems, and its management. The study will also recommend sustainable, environmentally safe control approaches that align with national agricultural development goals and international phytosanitary standards and to recommend sustainable, environmentally safe control approaches that align with national agricultural development goals and international phytosanitary standards. The study was conducted using secondary data compiled from Indonesia and international sources up to 2025.

METHODOLOGY

This review employed a systematic and structured literature review method to collect and assess information on bioecology, its incidence in Indonesia, and sustainable management, while also developing a comprehensive strategy for effective and

environmentally safe management. The methodology was designed to ensure comprehensiveness, credibility, and relevance to the scope of sustainable pest (*A. fragariae*) management in horticultural systems. The literature review began with the clear definition of research objectives and scope, focused on understanding the pest's biology, its current and potential impact on Indonesian agriculture, and identifying environmentally safe control methods. Subsequently, a variety of databases were selected, encompassing both national and international repositories. These included peer-reviewed scientific journals, official reports from Food and Agriculture Organization (FAO), World Health Organization (WHO), the Indonesian Directorate of Food Crop Protection, publications from the Indonesian Ministry of Agriculture, the Indonesian Ministry of Trade, the Indonesian Agency of Agriculture Quarantine, and online content from regional agricultural departments. International databases such as the CABI (2022) and EPPO (2022) were also consulted for updated global insights on *A. fragariae*. These platforms offered information on pest distribution, biology, regulatory status, and suggested control methods. Relevant records were downloaded and filtered based on date, credibility, and relevance to the Indonesian context. A total of 107 articles were screened. The search terms were meticulously selected and customized for each database to obtain the most pertinent outcomes. Keywords included "*A. fragariae*", "foliar nematode", "horticultural nematode management", "Indonesia", "biological control", and "sustainable pest control". Only literature types that met inclusion criteria such as primary studies, review articles, government publications, and validated technical documents—were retained. Subsequent screening involved reading titles, abstracts, and full texts where necessary to determine the applicability of each source. Data were manually extracted and categorized thematically into areas including nematode biology, distribution, economic impact, and control methods. Subsequent clarification of key concepts and definitions was performed to aid in comparative analysis. To ensure its quality and reproducibility, the research methodology process is ensured that the resulting review utilizes diverse, credible, and contemporary sources. It is methodologically grounded and suitable for informing policy, research, and practice in the sustainable management of *A. fragariae* in Indonesia. Flow chart of data exploration to recommendation and conclusion is presented as below (Table 1).

Bio-ecological characteristics of A. fragariae as an invasive species

The foliar nematode *A. fragariae* has been subjected to detailed morphological and molecular analyses to aid in its identification and differentiation from related species. According to Siddiqi (1975); CABI (2022); Kohl (2011); Wheeler and Crow (2020), these sources offer detailed morphological descriptions and microscopic diagnostics that set *A. fragariae* apart from similar nematodes. Key morphological features include a slender female body measuring approximately 0.46 to 0.70 millimeters (mm) in length and 15 micrometers (µm) in width, the presence of two lateral lines, and a tail that terminates in a pointed or spike-like tip. With a length of around 10 µm, the narrow stylet features small, well-defined basal knobs. An extensive metacorpus that aligns with the width of the esophagus is also found, together with a slightly protruding configuration of labial structures encircling the oral opening. The vulval region is situated approximately two-thirds along the body length. Male specimens closely resemble females in general body shape and size, although their tails tend to curve between 45° and 90° when relaxed and may end in a rose-thorn shape or display pronounced spicules. *A. fragariae* displays the features of invasive plant parasitic nematodes, namely, polyphagous, have a broad geographic range, exhibit a migratory ecto-endoparasite, an amphimictic mode of reproduction (bisexual), a short lifecycle with 10–11 days at 18 degrees Celssius (°C), and include survival adaptations like anhydrobiosis. Up to date, this nematode infects over 500 plants in about 100 families; these plants include dicots, monocots, gymnosperms, angiosperms, ferns, and mosses; in particular, approximately 100 fern species have been documented as hosts for *A. fragariae*, illustrating the nematode's high adaptability and host diversity (Kohl, 2011; Sturhan, 1962; Goodey *et al*., 1965; Stokes, 1967) (Table 2). Transmission of *A. fragariae* occurs via rain splash, the use of overhead sprinklers for irrigation, physical contact with infected foliage, and the planting of both infected and asymptomatic plants and seedlings (Wheeler and Crow, 2020; Djiwanti and Supriadi, 2011). Geographical records indicate that *A. fragariae* has been reported across

Table 1: Flow chart of data exploration to recommendation and conclusion

Data explorations	Output	Outcomes
Bio-ecological characters	Invasive characters	Recommendations to Indonesian Agricltural Ministry, researchers and growers in horticultuural agroindustry globally Conclusion: Proposed comprehensive approach of sustainable management strategies of foliar nematode
Damage	Potensial economical impact	
Effective control measures	Control measures: Preventive and curative measures, monitoring activities, availability of diagnostic tools and laboratories, equipment for control, involvement and collaboration among institutions and farmers	
Incidence in Indonesia	Historical evidences (2003 – 2025): infected host plants and locations (regions)	
Distribution and transmission	Infected seedling cultivations	
Horticultural pest problem for sustainable production	The foliar nematode has not been included as one of horticultural major pests to be controlled by directorate of plant protection	
Management systems	Early warning system (EWS) protocols for effective and safe management of horticultural major pests The foliar nematode has not been the target in EWS program of horticultural pest control	
References	Discussion of obtained outputs	Recommendation and conclusions

a broad range of regions worldwide, spanning five continents. *A. fragariae* has been reported across Asia, Europe, and North America, including both continental and island regions. It is also present in parts of Oceania, South America, the Middle East, and several countries in Africa and Central America (CABI, 2022). The foliar nematode *A. fragariae* has been reported across various regions of Indonesia. These distribution patterns illustrate the species' significant dispersal potential and its capacity to thrive in a broad spectrum of climatic and ecological environments (EPPO Global Database, 2022; Kohl *et al*., 2010). *A. fragariae* is a migratory ecto-endoparasite that lives as a saprophyte and plant parasite. As a saprophyte, it flourishes in soil or on decaying plant material and is likely to feed on fungal hyphae to sustain itself and reproduce (Goodey, 1963; Richardson and Grewal, 1993; Zhen *et al*., 2012). The incorporation of infected organic materials, such as decomposed symptomatic leaves and untreated animal manure particularly dried goat manure, it has been identified as a major contributor to the spread of *A. fragariae* in the cultivation of certain medicinal crops, such as *Andrographis paniculata* (king of bitters) (Djiwanti and Supriadi, 2011). In humid conditions, soil-dwelling nematodes travel up a plant through the water layer that envelops the stem, which results in the infection of new, healthy plants as the season progresses. They initially target the lower leaves. When infecting leaves, the nematode penetrates the epidermal layer with its stylet or enters through stomatal openings to feed on plant tissues, and lay eggs in the mesophyll layer and parenchyma cells of leaves and in leaf buds, causing cell death and discoloration (Desaeger and Noling, 2017; Klingler, 1970; Riedel and Larsen, 1974). The pronounced leaf discoloration was observed in the dieback disease affecting lilies due to the nematode (Yamada and Takakura, 1989). In king of bitters, interveinal chlorosis appears after about 14 days; the infected part turns brown, and water-soaked patches appear after around 30 days to form blotches (Djiwanti and Supriadi, 2011). Spots extend over the whole leaf, and leaf loss advances upward from the lower leaves. Infected plants exhibit

Table 2: The bio-ecological characteristics of *Aphelenchoides fragariae* as the invasive species

No.	The species characteristics	Bio-ecological nature of the nematode that support the characteristics of the invasive species	Sources
1.	Can survive without a host plants	*Aphelenchoides spp.* can survive for years by withstanding desiccation and osmotic stress, persisting in dried plant debris, dormant crowns, soil, or by feeding on fungal hyphae.	El-Saadony *et al.* (2021); Jagdale and Grewal (2006); Goodey (1963); Richardson and Grewal (1993); Zhen *et al.* (2012).
2.	Quickly reproduction	The nematode has a hort life cycle (10–11 days) at 18 °C. A single female can lay around 32 eggs, and a single leaf may contain up to 60,000 nematodes. *A. fragariae* has an amphimictic reproduction mode (bisexual). It possess both male and female reproductive organs and engage in cross-fertilization.	Singh *et al.* (2013a); Strumpel (1967). IPPC (2016).
3.	High adaptability to a wide diversity of host plants	The 100 plant families (covering about 500 species) include dicots, monocots, gymnosperms, angiosperms, ferns, and mosses were reported to be infected by *A. fragariae* include Liliaceae, Alstroemeriaceae, Acanthaceae, Haemodoraceae, Araceae, Asclepiadaceae, Aspleniaceae,Poaceae, Ericacea, Begoniaceae, Loganiaceae, Campanulaceae, Brassicaceae, Chenopodiaceae, Chloranthaceae, Dicksoniaceae, Convolvulaceae, Cornaceae, Asteraceae, Rosaceae, Moraceae, Malvaceae, Hydrangeaceae, Lamiaceae, Marantaceae, Osmundaceae, Peoniaceae, Apiacea, Piperaceae, Polygonaceae, Primulaceae, Rubiaceae, Pteridaceae, Gesneriaceae, Saxifragaceae, Dipsacaceae, Solanaceae, Caryophyllaceae, Boraginaceae, Scrophulariaceae, Violaceae, Caprifoliaceae, Labiatae, Anemiaceae, Aristolochiaceae, Araliaceae, Agavaceae, Amaranthaceae, Aracaceae, Alismataceae, Blechnaceae, Buddlejaceae, Barberidaceae, Balsaminaceae, Cabombaceae, Ceratophyllaceae, Cyatheaceae, Cyperaceae, Chloranthaceae, Crassulaceae, Cactaceae, Commelinaceae, Dryopteridaceae, Davalliaceae, Dennstaedtiaceae, Fabaceae, Geraniaceae, Gunneraceae, Grossulariaceae, Hyacinthaceae, Hydrocharitaceae, Hydrophyllaceae, Haloragaceae, Iridaceae, Lythraceae, Lentibulariaceae, Marattiaceae, Marchantiaceae, Musaceae, Melanthiaceae, Najadaceae, Orchidaceae, Onagraceae, Oleaceae, Oxalidaceae, Philesiaceae, Plumbaginaceae, Paeoniaceae, Polypodiaceae, Polemoniaceae, Pinaceae, Potamogetonaceae, Plantaginaceae, Ranunculaceae, Ruscaceae, Schizaeaceae, Strelitziaceae, Thelypteridaceae, Ulmaceae, Verbenaceae.	Kohl (2011); Khan *et al.* (2008); Sturhan (1962); Goodey *et al.* (1965); Stokes (1967); CABI (2022); Kohl (2011); Khan *et al.* (2008).
4	Extensive dispersal capability	*A. fragariae* is transmitted by rain splash, by overhead sprinklers, by planting asymptomatic infected plants, and through physical contact with infected leaves. For wider distribution, *A. fragariae* may infest plant parts, including underground organs, floral structures, foliage, seedlings, stems, branches, seeds, and even the growing medium, during trade or transportation to other regions or or countries.	Wheeler and Crow (2020); Djiwanti and Supriadi (2011). CABI (2022).
5.	Its adaptability to a wide range of climatic and ecological conditions	*A. fragariae* has been reported across regions covering five continents, i.e. Asia (China, India, Indonesia, Israel, Japan, Kyrgyzstan, South Korea, Turkey, Vietnam), Europe (Belgium, Bulgaria, Denmark, Estonia, France, Germany, Hungary, Ireland, Italy, Latvia, Moldova, Netherlands, Norway, Poland, Portugal, Russia, Serbia, Slovakia, Spain, Sweden, Switzerland, Ukraine, United Kingdom), North America (Canada Cuba, Mexico, United States), Oceanea (Australia, New Zealand, Papua New Guinea), South America (Brazil, Chile), countries of the Middle East, North and Central Africa, and Central America (Fig. 1).	CABI (2022); EPPO Global Database (2022); Kohl *et al.* (2010); Ferris (1999).



Fig. 1: The Worldwide distribution map of *Aphelenchoides fragariae* (CABI, 2022)

reduced flowering and fruit set, twisted or malformed buds and blooms, reddened leaves, small curled or crinkled foliage (crimp), and stunted growth. In *Lantana camara*, indications of infection start to show when the density of nematodes reaches around 10 nematodes/g of foliage (Kohl *et al.,* 2010). Infection of anthurium seeds by this nematode has been reported (Hunter *et al.,* 1974), although symptoms are often not visible when nematode levels remain low (Lehman, 1996). This nematode reproduces very quickly. A single female can lay around 32 eggs, which hatch and begin to multiply in 10 days. A single leaf may contain up to 60,000 nematodes. Under an 18 °C regime, the nematode achieves a full life cycle within 10–11 days on begonia leaves (Strumpel, 1967). The *Aphelenchoides* spp. have also an amphimictic mode of reproduction (bisexual). Many species within the *Aphelenchoides* genus, including *A. fragariae*, reproduce bisexually. This signifies that they contain both male and female reproductive organs and are involved in cross-fertilization (IPPC, 2016). After hatching, J2 juveniles immediately feed on the adjacent cells. For temperate species (*A. fragariae* and *A. ritzemabosi*), the ideal temperature range for nematode development is 21-24 °C equal to 70-75 Fahrenheit (°F) (Ferris, 1999). Yamada and Takakura (1987) observed that nematode numbers in lily foliage swell during the rainy season. Szczygiel and Hasior (1972) reported that populations of *A. fragariae* and *A. ritzemabosi* reach their highest levels in the cool, humid conditions of early spring. Wallace (1960) also observed that adult (J4) nematodes leave the leaf and move onto the plant surface whenever a moisture film, created by rain, irrigation, or morning dew, develops. A moisture film will elevate relative humidity for attribute nematode mobility and survival on the host's exterior (Jagdale and Grewal, 2006). In the spring, before moving on to fresh leaves, the nematodes hibernate under the soil, Jagdale and Grewal (2006) also detected nematodes in dormant crowns as well as in abscised leaves. When free moisture is present, the foliar nematodes that have entered a state of anhydrobiosis in the soil can reactivate; alternatively, they adopt a cryptobiosis strategy, suspending their metabolism and remaining dormant until optimum conditions return (El-Saadony *et al.*, 2021). The nematode is evidently adapted to flourish in both tropical and temperate climates (Ferris, 1999). The ability of foliar nematodes to overwinter in arid soil, fallen leaves, and dormant bud's likely stems from their resilience to desiccation and osmotic stress. In warm and humid soils, such as those found in tropical Indonesia, nematode populations can quickly multiply (Djiwanti

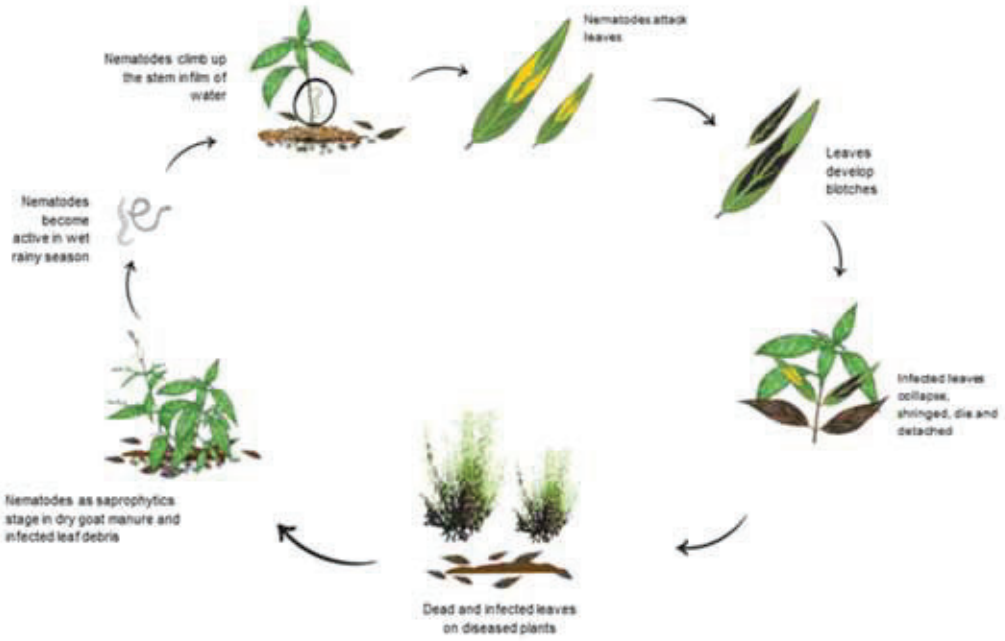

Fig. 2: Life cycles of foliar nematode *Aphelenchoides fragariae* on medicinal plant *Andrographis paniculata* (king of bitters)

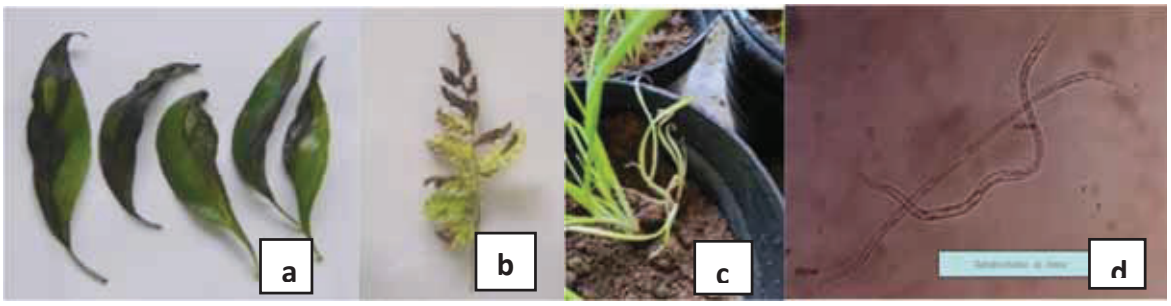

Fig. 3: Symptoms and damages caused by *Aphelenchoides fragariae*. 3a. Leaf blotch on a king of bitters plant leaves. 3b. Blotch on fern frond. 3c. Plant wilt on a shallot young plant raised from an infected bulb. 3d. Adult female and male *A. fragariae* isolated from an infected king of bitters plant leaf

and Supriadi, 2011). Life cycles of foliar nematode *A. fragariae* on medicinal plant *A. paniculata* is presented (Fig. 2).

Incidence of A. fragariae in Indonesia

Historical evidence

Aphelenchoides was first detected in Indonesia on medicinal plant *A. paniculata* (king of bitters) in the fields, nurseries and greenhouses in 2003 (Fig. 3d). Plants that are infected display symptoms of leaf blotch, including dark brown to black spots along the veins of the leaves, leading to the defoliation of seedlings as well as mature plants (Fig. 3a). In moderate to severely infected leaves of king of bitters, the nematode population may reach around 15.440 vermiforms (Djiwanti and Supriadi, 2011). In Bogor, located at approximately 300 meters above sea level in tropical Indonesia, *A. fragariae* was observed to induce severe symptoms during the wet season (around October to April) (Djiwanti and Supriadi, 2011). The nematode-affected weeds grown in the field and in polybags in and around plantations of king of bitters include *Ageratum conyzoides*, *Acalypha lanceolata*, *Oxalis sepium*,

Borreria sp., *Lindernia sp*., and fern *Pleocnemia sp*. (Fig. 3b) (Djiwanti and Supriadi, 2011). Since then, foliar nematode-infected king of bitter plants was reported in other some locations in Java in 2012, in 2013, and in 2018 (Kementan, 2020a). *A. fragariae* has been targeted in regulatory programs. According to Regulation No. 25/2020 by the Indonesian Ministry of Agriculture concerning quarantine plant pest organisms (Kementan, 2020a), this nematode is classified as an A2 quarantine pest. This category consists of plant pests that have taken root in Indonesia, yet are confined to particular locations. Since then, *A. fragariae* was regularly reported on other host plants in surveys across different locations conducted by Barantan (Indonesian Plant Quarantine Agency). This nematode was intercepted during a quarantine inspection at the BBKP (Balai Besar Karantina Pertanian/ Agricultural Quarantine Major Service) in Surabaya, East Java, *A. fragariae* in garlic bulbs imported from China (Kementan, 2020a). This nematode has also already been reported in some regions of the garlic area center in Central Java Kementan (2020a) detected *A. fragariae* in shallot bulbs at the market and in shallot plantations. Kurniawati *et al*. (2025) reported cases of *A. fragariae* infestation in strawberry plants. Phylogenetic studies indicate that the three isolates of the Indonesian king of bitter plant are 98.20–100 percent (%) similar to *A. fragariae* isolates found in multiple countries (Djiwanti and Miftakhurohmah, 2022).

Potential economic impact of A. fragariae to the horticultural agroindustry in Indonesia

Horticultural crops as potential agroindustry in Indonesia

Numerous horticultural products are in significant demand and are advantageous for exporting to several countries. In Indonesia, the horticultural commodities offer great business opportunities in both domestic and international markets through import–export trading. Advancements in the horticultural industry encompass the cultivation of vegetables, fruits, ornamental plants, and medicinal plant products, primarily focused on enhancing farmers' income and improving their welfare, while also boosting profits for entrepreneurs and expanding the country's foreign trade. Indonesia has strong potential for strawberry, ornamental plants, shallot, and garlic exports, supported by high domestic and international demand. To meet this, Indonesia has improved horticultural production in both quantity and quality. Strawberries from Indonesia are routinely sent to other regions in Indonesia, and to Malaysia, and Saudi Arabia, the United States, Japan, and South Korea (Maarif, 2021). For ornamentals, key products include chrysanthemums, orchids, Dracaena, gerbera, ferns, and Araceae species such as Philodendron and Anthurium. Major export destinations are Japan, the Netherlands, Singapore, and other markets in Asia, Europe, Australia, and North America. In 2021, the exported items included rootless orchids, cut flowers, lilies, orchid seedlings, and chrysanthemums, with a marked rise in the demand for ornamental leaf plants. The demand for ornamental leaf plants grew by 15.84% and reached about USD 1.67 million during the first semester of 2021 (Diskominfo Jatim, 2021). For vegetable crops, shallots and garlic are key strategic commodities being developed to reduce high import dependence. To lessen the heavy dependence on imports, shallots and garlic are vital strategic commodities being cultivated for vegetable crops. Initiatives have been undertaken to boost shallot and garlic output by expanding the cultivation areas in provinces that have optimal conditions. Shallots provide an income source and employment opportunities, contributing significantly to regional economic development (168 million USD per year) (Idris, 2015). The consumption demand for shallots, whether for eating, seed supply, industrial applications, and export needs, is steadily growing. Thailand, Singapore, Malaysia, Vietnam, South Korea, Hong Kong, and Taiwan import Indonesian shallots (Kemendag, 2019). Indonesia currently imports garlic mainly from China, India, Taiwan, and the United States (Kementan, 2020b). Indonesia produces garlic as an import substitute. How ever, due to its high allicin content, South Korea, Hong Kong, Singapore, Taiwan, and Vietnam all import Indonesian garlic.

Foliar nematode as potensial damage and economic loss on horticultural crops

The production and quality of horticulture are frequently compromised by shifts in ecosystems and agricultural practices, particularly due to climate change, which alters pest dynamics and the balance of natural predators. The incidence of *A. fragariae* has recently increased with the expansion of shallot and strawberry production, as asymptomatic

Table 3: The Damage and potential economic loss of the foliar nematode *Aphelenchoides fragariae* infestation on horticultural agroindustry

No.	Damage	Loss	Sources
1.	Yield loss	*A. fragariae*-associated leaf blotch caused 60–80% defoliation of king of bitters, especially in the rainy season.	Djiwanti and Supriadi (2008, 2011);
		Yields fell 65% and 82% for Macherauchs Frühernte and Cambridge Favorite in Poland after two years.	Szczygiel (1963); Clerjeau *et al.* (1983).
2.	Quality deterioration	Rotting shallot bulbs in the market (that sell for consumption).	Styaningrum, 2018
		Leaf nematode infections reduce the attractiveness, production, and quality of ornamental plants such as chrysanthemums, gerberas, ferns, Dracaena, and anthuriums, making them less marketable.	Goodey *et al.* (1965); Hunter *et al.* (1974).
		Currently, it is quite challenging to find truly healthy king of bitters seedlings that are free from *A. fragariae* infection. On a shallot bulb, some of the dead plants in polybags that were raised from asymptomatic infected bulb seeds were detected.	Author's observations in a nursery and greenhouse
3.	Infested/contaminated plant seeds, seedlings, marketed yield, and soil	Planting bulbs or seedlings infested with *A. fragariae* can introduce the nematode into previously nematode-free areas. Its incidence has risen recently with the expansion of shallot and strawberry production.	Kementan (2020).
		Infestations may trigger export rejections and shipment returns, causing potential revenue losses of millions of dollars. Its introduction into nematode-free areas may also increase infection sources in the field.	CABI (2023); Jagdale and Grewal (2004).
4.	Secondary bacterial co-infection worsens disease and damage.	*A. fragariae* worsens Xanthomonas leaf blight on Rieger begonia and, with *Pseudomonas cichorii*, has damaged *Barleria cristata* nurseries.	CABI (2023); Riedel and Larsen (1974); Lehman and Miller (1988).
5	Difficult to eliminate once the foliar nematode has established itselves in the nursery and field	Increase financial input in crop production of additional nematode management inputs in cultivation.	Kohl (2011).

planting materials such as cuttings, seedlings, and bulbs can introduce the nematode into new areas. Its spread into nematode-free regions can worsen yield losses, reduce quality, and expand infections to previously unaffected hosts (Table 3). The existing damage indicators consist of a higher occurrence of leaf nematode detection in decaying shallot bulbs found within traditional markets, as well as in plants exhibiting yellowing to light browning in polybags that were grown from infected seed bulbs (according to the author's author's greenhouse observations) (Fig. 3c). Although *A. fragariae* can cause economic losses, its actual impact in Indonesia has not been assessed. The nematode is a challenge to the cultivation of king of bitters, a medicinal plant widely used in traditional medicine. However, losses remain unknown due to the plant's limited cultivation and the nematode's restricted distribution in West Java. However, based on research on the use of nematicides against *A. fragariae*, nematodes cause the defoliation of king of bitters in around 60–80% of seedlings grown in polybags and in plants grown in the field, especially during the rainy season (Djiwanti and Supriadi, 2011). In Bogor, where *A. fragariae* was first detected, it is difficult to obtain healthy king of bitters seedlings free from infection, showing how quickly the nematode can spread across planting areas. Similar problems have been reported abroad, with yield losses of up to 65% in Macherauchs Frühernte strawberries in Poland and 82% in Cambridge Favorite in France (Szczygiel, 1963; Clerjeau *et al*., 1983). In the United States, annual reports indicate that foliar nematode infestations occur in greenhouses, nurseries, and garden centers, resulting in substantial damage for both ornamental and food crops. Outbreaks have increased as most chemical pesticides are no longer registered for floriculture, and in Florida, crimp disease in strawberries has been linked to the discontinuation of methyl bromide fumigation in transplant nurseries (Desaeger and Noling, 2017). The financial consequences of the absence of these management tools (chemicals) for the plant

industry as a whole are hard to estimate, and there is a notable deficiency of data about existing losses (Wheeler and Crow, 2020). Infestations often occur alongside other pathogens, increasing leaf fall. If *A. fragariae* infects plants along with bacterial pathogen Xanthomonas and *Clavibacter* spp., then *A. fragariae* can enhance the incidence and severity of diseases symptoms caused by the bacterial (CABI, 2022). On Rieger begonia, infection by *A. fragariae* can increase both the occurrence and intensity of leaf blight diseases caused by the bacterial *Xanthomonas begonia* (Riedel and Larsen, 1974). *A. fragariae* and *Pseudomonas cichorii* complex disease were observed and destroyed *Barleria cristata* (Lehman and Miller, 1988). Foliar nematodes on ornamental reduce their marketability; Infestation of pests (insects, fungi, mites, nematodes) are a common cause of export rejection. From 2014–2022, notifications of non-compliance show rejections were mainly due to pest interceptions (60%), administrative issues (22%), and prohibited items (18%) (Indahsari *et al.,* 2024). The foliar nematode is recognized for its substantial phytosanitary significance, attributed to its extensive host plants and its potential to result in significant financial damages (Singh *et al*., 2013a). The regulatory programs around the world target *A. fragariae* (O'Bannon and Esser, 1987). Pest infestations, such as those caused by *A. fragariae*, can lead to the rejection of flower shipments and interfere with trade operations. This nematode may attack various plant parts, including roots, stems, leaves, flowers, seeds, seedlings, and even growing media during transport or trade (CABI, 2022). Reports indicate that *Aphelenchoides* nematodes are present in compost found in an organic growing medium (Mani, 1998). In the ornamental plant industry, Indonesia is the highest producer of chrysanthemums, roses, tuberose, gerbera, ferns, orchids, Phylodendron, Dracaena, and anthurium flowers (Diskominfo Jatim, 2021). As hosts for *A. fragariae*, several ornamental plants, such as chrysanthemums, gerberas, ferns, Dracaena, and anthuriums are affected by leaf nematode infections both in terms of production and quality of commodities (Goodey *et al*., 1965; Hunter *et al.,* 1974; Karantina Jakarta, 2023 *in* Indahsari *et al*., 2024). Chrysanthemums, orchids (Orchidaceae), and *Gerbera jamesoni* can serve as hosts for *A. fragariae* (Esser *et al*., 1988; Goodey *et al*., 1965). Returning shipments that include contaminated plants may cause a financial loss amounting to millions of dollars (Jagdale and Grewal 2004). Exporting Indonesian ornamentals and horticultural products, including ferns, Dracaena, shallots, garlic, and strawberries, could result in rejection upon detection of foliar nematodes. In Indonesia, *A. fragariae* was reported to associate with those plants.

Plant protection program implemented by the indonesian government for horticultural production areas and its suggestion for foliar nematode

The Ministry of Agriculture of Indonesia encouraging farmers to increase the cultivation and production of quality seeds, and by ensuring that global export quality standards are met. The Indonesian Ministry of Agriculture is advancing export horticulture through initiatives in regional development, enhancements in seed quality, and the application of EWS-based pest monitoring, a program that has already seen success with shallot and garlic (Diskominfo Jatim, 2020). Plant protection currently targets the major pests in shallot and garlic plants, such as purple spot/trotol fungus (*Alternaria porii*) and fusarium wilt fungus (*Fusarium oxysporum*) during the wet season, and leaf caterpillar (*Spodoptera exigua*) during the dry season. EWS aims to reduce the use of chemical pesticides. The monitoring of pest and disease infestation levels, as well as climate conditions, is conducted through careful observation and continuous reporting to the aforementioned agencies, enabling the determination of effective control strategies to be implemented (Diskominfo Jatim, 2020). The Directorate promotes pest control through the IPM system with guidance and support. At 25% infestation, measures include healthy cultivation, resistant pest-free seeds, and seed dipping with plant growth-promoting rhizobacteria (PGPR) or *Trichoderma spp*. to suppress soil-borne diseases, along with sticky, pheromone, light traps, and shading nets. Biological control materials are available from regional pest and disease labs. At 50–85% infestation, chemical control is applied. Even though *A. fragariae* is not currently a focus for control, it is recognized as an A2 quarantine pest that requires monitoring. It is essential to keep stakeholders updated on detection methods, symptoms, host range, transmission, and control measures. Being a category A2 quarantine plant pest, anticipatory management of *A. fragariae* is needed to control the *A. fragariae* population and its

Table 4: Effectivity of some botanicals, new generation pesticides, and chemicals against *A. fragariae* population suppression

Classification	Pesticide ingrediants	Effectivity	Advantages/ disadantages	Sources
Botanical pesticide	Neem seed powder (NSP)	10–15 g/plant effectively suppressed the nematode population in the leaves of king of bitters by as much as 97.54–100.00%.	Effective and eco-friendly control method	Djiwanti and Supriadi (2011).
	Water extract of NSP	A 0.5-1.0% water extract of NSP suppressed nematode population in the leaves of king of bitters as much as 99.87%.	Effective and eco-friendly control method	Djiwanti and Supriadi (2011).
	CNSL	0.5-1.0% liquid suppressed nematode population in the leaves of king of bitters as much as 100%.	Effective and eco-friendly control method	Djiwanti and Supriadi (2011).
	Essential oils mixture (32% cinnamon oil, 8% clove oil, 15% thyme oil)	At low concentration (20-fold dilution) in a soil drench and a leaf spray application showed 100% mortality of *A. fragariae* in anemone (plants with thin leaves).	Effective and eco-friendly control method	An *et al.* (2017).
New generation pesticides	chlorfenapyr	At low concentration (20-fold dilution) Pylon (24% chlorfenapyr) showed 100% mortality of *A. fragariae* in a soil drench and a leaf spray application in plants with thin leaves, such as anemone.	Effective, however challenges and limits still exist in issues of the resistance, residual toxicity to non-target organisms and in-depth mechanism exploration.	An *et al.* (2017); Huang *et al.* (2023).
Chemicals	corbofuran	2.0-5.0 g/plant suppressed 100% nematode population in leaves of king of bitters.	Effective, but not eco-friendly control method	Djiwanti and Supriadi (2011).

wider spread in horticultural production areas. Some preventive strategies have been implemented such as using the healthy and pest-free superior horticultural varieties, and by the Agricultural Quarantine Major Services such as using molecular tools for the accurate detection of the nematode incidence and intercepting the nematode that infested in horticultural imports. Additionally, the application of neem seed powder and its aqueous extract, as well as cashew nutshell liquid (CNSL), can be proposed as suppressive strategies (Table 4). Future suggestions for *A. fragariae* in Indonesia, the nematode should be included (besides major pest's purple spot fungus *A. porii*, fusarium wilt fungus *F. oxysporum*, and leaf caterpillar *S. exigua*) in the observation and monitoring as part of an EWS program in central production areas, as implemented by the Directorate in order to take early action for biological control of the nematode. To effectively apply it in the field, the nematode must be incorporated into the technical "guidelines for observing and reporting plant pests and the impacts of climate change" that published by the Directorate. The Indonesian Agricultural Quarantine conducts routine surveillance and mapping of nematode detection areas and published a Regulation of the Indonesia Ministry of Agriculture concerning Quarantined Plant Pest Organisms. Based on this publication, the Directorate of Food Crop Protection should observe and monitor horticultural crops as EWS in infected areas more intensively and apply biological control method if the infection reaches 25%, and only take horticultural plant seeds/seedlings from free areas. Furthermore, the Agricultural Quarantine carries out inspections on incoming imports at specified ports and takes action if foliar nematodes are found; as a result, it will help stop the nematode from spreading across Indonesia.

Control measures for A. fragariae

Various control methods from preventing to controlling foliar nematode infestations have been evaluated and shown to be effective in managing

A. fragariae population. An effective and practical control strategy focuses on the early identification and elimination of this pest from growing environments. This strategy utilizing propagative stock that is free of nematodes (McCuiston *et al.,* 2007). Control measures for *A. fragariae* may include strategies for effective management, such as monitoring and early detection of nematodes, plant certification, implementing cultural control methods, utilizing physical, applying biological control techniques, adopting resistant varieties, and employing chemical control measures.

Nematode early and rapid detection

Precise identification is essential for assessing nematode diversity and for formulating effective control and management strategies. Utilizing morphological analysis alongside the existing deoxyribonucleic acid (DNA) sequence data enhances the precision of *A. fragariae* identification. Molecular tools, such as polymerase chain reaction (PCR), can also be used to confirm the identification of *Aphelenchoides* species isolated from plant and soil materials. *A. fragariae* detected in a host plant can be identified early using the ITS-1 PCR diagnostic assay (McCuiston *et al*., 2007; Djiwanti and Miftakhurohmah, 2022). To quickly identify the foliar nematodes found in soil and plant samples, species-specific primers based on small subunit (SSU) ribosomal DNA were developed for four *Aphelenchoides* species including *A. fragariae* (Rybarczyk-Mydłowska *et al*., 2012). Most reports on *Aphelenchoides* molecular analysis were also based on 18S (rRNA) rDNA, 28S, and COI (Chizhov *et al*., 2006; Kanzaki and Futai, 2002; Sánchez-Monge *et al*., 2017; Kurniawati *et al*., 2025). In regulatory laboratories, where precise identification is required for phytosanitary permits, the *A. fragariae*-specific PCR assay may be used to help growers screen plant materials for early detection of foliar nematodes. Furthermore, it can be employed to research the biology of *A. fragariae* to advance and formulate improved strategies for the management of foliar nematodes.

Cultural control

The important components of cultural management programs include elimination and disposal of diseased plants and abscised leaves in pots or on the ground, and sterilization of pots, soils, and equipments (trowels, pruning shears, pruning saws, and scissors) by baking or steaming them at 180-200 °F (82.22 - 93.33 °C) for 30 minutes (min.) (Illinois Extension, 2000), avoiding misting and sprinkler irrigation (which can hasten the spread of nematodes) (Young, 2000; Zhen *et al.,* 2012), switching to wheat or broccoli for plant rotation, and incorporating the crop residue into the soil (Ploeg and Westerdahl, 2018; Yamada and Takakura, 1987). The cultural management strategy for the nematode also encompassed fallowing the field and disposing of infected plants (Ploeg and Westerdahl, 2018).

Plant certification

Healthy plant production is an important step in the prevention and control of *A. fragariae* infection. The endeavor to generate healthy plants and seedlings involves plant certification systems and physical interventions. Plant certification programs for clean strawberry stocks have effectively prevented the introduction and spread of *A. fragariae* and *A. ritzemabosi* (Tacconi and Lamberti, 1994). A certification initiative was launched to provide a supply of true-to-type strawberry plants free of viral infections and foliar nematode species (*A. besseyi*, *A. blastophthorus*, *A. fragariae*, and *A. ritzemabosi*) (EPPO/OEPP, 2008). The standard outlines the production of certified pathogen-tested strawberry material. At all certification stages (nuclear, propagation I and II, and certified stock), zero tolerance for *A. fragariae* is enforced during visual inspection. In cases where no cultivar or clone is free from nematodes, it is imperative to apply treatments to eliminate the pest. According to Tacconi and Lamberti (1994), this scheme has protected strawberry plantations for at least eight years and has delivered very satisfactory results.

Physical control

Physical treatments to produce nematode-free plant stock and to control the nematode in plantations include HWT (hot water treatment) of aerial plant parts (leaves), plants/seedlings, runners, and dormant plant materials (bulbs and buds), as well as exposure of diseased plants to woodlight (300–400 nm) and to a combination of woodlight and blue or white light continuously or for 12 h per day, and hot water drench (Jagdale and Grewal, 2004; Kohl, 2011;

Mitiku, 2018; Moussa, 1972). HWT at 47 °C for 15 min has been suggested for strawberry runners (Strümpel 1969) and at 46 °C for 10 min before a cool plunge (MacLachlan and Duggan, 1979). *A. fragariae* was successfully removed from five strawberry cultivars (Chandler, Douglas, Fern, Pajaro, and Selva) in 20-30 minutes at 44.4 °C, 10-15 minutes at 46.1 °C, or 8-10 minutes at 47.7 °C, with no harmful effects on the cultivars (Qiu *et al.*, 1993). Dormant buds of nematode-infested lily bulbs may be treated for 20-30 min at 45 °C (Yamada and Takakura, 1989), for 1 h at 41 °C, or for 6 h at 36 °C (CABI, 2022) and for 1 h in a hot water formaldehyde bath (1 pint of 38% formaldehyde in 25 gal of water) at 44 °C (Jensen and Caveness, 1954). HWT at 46 °C for 10 min eliminated *A. fragariae* and *A. ritzemabosi* from Lorraine begonia (Rasmussen, 1971). Moreover, HWT at 47 °C for 40 min applied to tree peonies in November in Japan completely eliminated *A. fragariae* (Saigusa, 1968). Cuttings can be sterilized by immersing them in hot water for 5 min at 50 °C (122 °F) or for 30 min at 44 °C (111 °F) (Desaeger and Noling, 2017). Newly treated plants must be kept in quarantine in a nursery for several weeks before being planted in the field, allowing for the observation of any symptoms that may arise. HWT is commonly used in plant quarantine to produce nematode-free plant materials for export (Kementan, 2020a). In the temperate nations, the application of a 90 °C water drench in the fall significantly reduced the foliar nematode population in the soil and lowered the count of nematode-infected leaves per plant in the summer (Jagdale and Grewal, 2004).

Adopting resistant cultivars

A comprehensive management approach for foliar nematodes includes the use of resistant and tolerant plant varieties (Jagdale and Grewal, 2006). Utilizing resistant varieties that are currently available is a highly effective strategy for minimizing crop yield losses by suppressing nematode population density at the damage threshold (Alves *et al*., 2017). Resistance against *A. fragariae* has been observed in some cultivars of strawberry, hosta, and begonia (Siddiqi, 1975 in CABI, 2023; Jagdale and Grewal, 2006). The strawberry cultivars 'Saksonka' and 'Festival'naya' in Russia, as well as 'George softwedel', 'Regina', and 'Talizman' in Poland, are relatively resistant (Szczygiel, 1963, Szczygiel, 1967; Amstrong and Jensen, 1978). Numerous cultivars of Rex begonias, including Shirt Sleeves, Merry X-mas, Winter Queen, Little Pet, Lucille Claussen, Fairy, Vesuvius, Tried and True, Helen Treupel, and Helen Lewis, appear resistant to foliar nematodes (Peirson, 1974 *in* Lehman, 1989).

Biological control

Biopesticides from beneficial microbes and plant extracts are being studied for sustainable management of *A. fragariae*. These alternatives, which do not involve chemicals, utilize natural resources like plants, animals, antagonistic microbes, bacteria, or minerals. They offer a promising biological control strategy for plant–parasitic nematodes (US EPA, 2024). Using a biopesticide prepared from dead plants infected with the beneficial microorganism *Galleria mellonella* by homogenizing it in soil medium, Jagdale and Grewal (2008) successfully prevented the growth and spread of *A. fragariae* in soil and reduced the lesions in infested hosta 30 and 40 days after application. Infected hosta leaves and the surrounding soil saw a 50–85% decrease in *A. fragariae* population when Rhizobacterium (*Burkholderia cepacia*) was applied to the foliage (Jagdale and Grewal, 2002). Neem seed powder and its water extract, along with CNSL (cashew nutshell liquid) and Nemakill (essential oils 32% cinnamon oil, 8% clove oil, 15% thyme oil mixture) were tested, and they effectively suppressed *A. fragariae* population when applied via the soil application method (Djiwanti and Supriadi, 2011; An *et al*., 2017). Nonetheless, numerous neem-derived pesticides and nematicides are harmful, and although they can decrease foliar nematode populations in strawberries by as much as 70–85%, none are capable of fully eliminating nematodes once they have established themselves in the soil (Akhtar and Mahmood, 1994; An *et al*., 2017). Azadirachtin, a bioactive ingredient in neem, functions as an antifeedant; it also inhibits molting, affects fecundity, and disrupts respiration and oviposition (Howard *et al*., 2009; Khalil, 2013; An *et al*., 2017).

Chemical control

Chemical control of *A. fragariae* involves fumigants, non-fumigants, and induced systemic resistance (ISR) agents, used only in heavily infested fields to suppress populations and prevent spread. Old-generation organophosphates and carbamates were once effective but are now limited by safety and

regulatory restrictions (Strider, 1973; Siddiqi, 1975 in CABI 2022; Djiwanti and Supriadi, 2011). As a result of legal limitations and environmental issues, numerous compounds are no longer accessible in certain countries. Recently, new non-fumigant nematicides are either being introduced or are in the registration phase as next-generation pesticides (NGPs), characterized by reduced toxicity to non-target organisms and enhanced control efficacy (Oka, 2020). These nematicides include proxy-acetic acid, chlorfenapyr, insecticidal soap, spirotetramat, fluensulfone, and fluopyram. Other environment-friendly insecticidal soap and the safer abamectin have also been shown to be effective against *A. fragariae*. Proxy-acetic acid is an organic compound commonly utilized as a disinfectant for protected horticultural crops, as well as an eco-friendly fungicide or algicide that has been approved (Cristofari-Marquand *et al*., 2007). Among its applications is the elimination of pathogens from benches and floors in between crops. When proxy-acetic acid was used as a foliar spray, the nematode population in infected hosta leaves considerably decreased 45 days after treatment (Jagdale and Grewal, 2002; An *et al*., 2017). Miticide chlorfenapyr is another new chemical that has been approved for the management of foliar nematodes in greenhouse ornamentals. Studies have demonstrated that chlorfenapyr can successfully lower foliar nematode numbers in thin-leaved plants, including anemone, but it proves to be less effective in thicker-leaved crops like Lantana (USDA, 2004). Chlorfenapyr is a pro-insecticide derived from halogenated pyrroles, first developed by American Cyanamid from Streptomyces fumanus. Once the host is entered, it transforms into an active form that hinders the production of adenosine triphosphate (ATP), causing the death of cells and the organism as a whole (Black *et al*., 1994). However, in 2005, the U.S. EPA has established a safe threshold for the presence of chlorfenapyr residues in or on any food product. Spirotetramat is another new and effective insecticide and potential nematicide. It has been proven to move through the phloem and xylem across several crop species, and it works systemically inside a plant (Smiley *et al*., 2011a; Smiley *et al*., 2011b). Spirotetramat may affect nematode reproduction and fertility even if it does not directly act against nematodes, and it effectively manages *A. fragariae* in various ornamental plants (Rotifa, 2019; Vang *et al*., 2016). Moreover, insecticidal soaps (fatty acid products) effectively control *A. fragariae* 48 days following foliar spray application (Jagdale and Grewal, 2002). Insects with delicate bodies, including nematodes, suffocate when insecticidal soaps damage their cell membranes, although soaps are generally safe for humans and animals. Fluensulfone and fluopyram have recently been recognized as the two foremost and most promising next generation nematicides (Oka, 2020; Desaeger and Noling, 2017). They have been used to control *A. fragariae* in Florida strawberries (Desaeger and Noling 2017). Fluensulfone sets itself apart from older nematicides by causing irreversible paralysis, which is triggered by its nematicidal component (Oka *et al*., 2009; Oka and Saroya, 2019). However, it affects and paralyses nematodes much more slowly than organophosphates (Oka, 2020) or fluopyram (Oka and Saroya, 2019). Nevertheless, there are still obstacles and restrictions, particularly when it concerns the issues of environmental toxicity and pest resistance (Huang *et al.,* (2023). Abamectin is another systemic insecticide as well as an anthelmintic, acaricide (miticide), and nematicide that proved effective and safer against *A. fragariae* (Putter *et al*., 1981). Abamectin (avermectin B1) is byproduct of fermentation of soil dwelling actinomycete Streptomyces avermitilis (Ikeda *et al*., 2003; Campbell, 2012). Applying abamectin to the foliage successfully controls *A. fragariae* infestations in different ornamental plant species. (Rotifa, 2019). Abamectin exhibits low solubility in water, which leads to a reduced potential for leaching across various soil types (Litskas *et al*., 2013; Dionisio and Rath, 2016). It disintegrates through photodegradation in aquatic environments, organic plant waste, soil, and the surfaces of plants (Halley *et al*., 1993), resulting in its low toxicity. The plant elicitor acibenzolar-S-methyl (ASM), which can trigger ISR during plant–pathogen interactions, is also an efficacious control agent against *A. fragariae*. El-Saadony *et al*., (2021) demonstrated that utilizing ASM and the extract from *Reynoutria sachalinensis* in both greenhouse and commercial field settings is warranted because of their ability to suppress the multiplication of *A. fragariae*, whether used individually or in conjunction with other pesticides. Compared with the control, ASM + spirotetramat decreased the *A. fragariae* population by 97% in Buddleja plants and by 95% in

Japanese anemone plants (Rotifa and Evans, 2021). The application of fumigants for soil disinfestation was also part of chemical control. This technique is vital for ensuring that plantations remain healthy and free of *A. fragariae*. Certified nematode-free planting materials can be produced in fumigated fields. Presently, drip fumigation covers more than 55% of the strawberry acreage in California (UC IPM, 2018). Their use requires county agricultural commissioner approval, and application must comply with California Restricted Materials Requirements and label rate limits (Ploeg and Westerdahl, 2018).

Regulations

Regulations, particularly on the application of chemical agents, are needed for the safe, effective, and efficient management and control of *A. fragariae*. Agrochemicals should be applied only when no alternative measures are available. Pesticides (and herbicides) that are permitted should only be utilized when required, and they should be used at the lowest effective level as indicated on the product label, package insert, or other instructions, in accordance with any applicable regulations in the country where the grower and end user are based (WHO, 2003). The list of registered pesticides legally permitted for use vary across countries and should be consulted when considering chemical control. The application of drip fumigation to heavily infested soils via drip irrigation should only be conducted once a year and following consultation on the use of fumigation (Ploeg and Westerdahl, 2018). In California, the use of fumigants such as 1,3-dichloropropene or chloropicrin in strawberry fields requires county agricultural commissioner approval, and application rates must comply with California Restricted Materials Requirements and product labels (Ploeg and Westerdahl, 2018). Despite the application of chlorfenapyr, a modern pesticide considered safer than its predecessors, the U.S. EPA has set a safe limit for the allowable residues in or on any food product (US EPA, 2001). Regulation/ law is also applied in the enforcement of plant quarantine measures at both the farmer and governmental levels. The Plant Quarantine Agency can limit the spread of *A. fragariae* by conducting inspections, isolation, observation, treatment, detention/ interception, rejection, destruction, and release of pest-free products inspected in quarantine outposts (Kementan, 2020a). During a quarantine examination at the port of Surabaya, Indonesia, *A. fragariae* was found in garlic bulbs imported from China (Kementan, 2020a). Products bound (such as carrier media) for export, import, or domestic trade are also inspected; the products are sampled, tested, and destroyed if found to be infested with pathogens.

Development of a comprehensive management strategy for A. fragariae

Inability to manage *A. fragariae* can be linked to its cryptobiosis strategy, its capacity to thrive in saprophagous forms within soil, and its resilience to desiccation and osmotic stress. Although sustainable non-chemical methods are preferred, they may be insufficient under severe infestations. Therefore, an integrated pest management (IPM) approach that combines compatible strategies is recommended to improve nematode control while reducing pesticide use and minimizing risks to human health and the environment (Rotifa and Evans, 2021). Utilizing both soil treatments and foliar applications for plants is recommended, as nematodes can migrate from infested media to unaffected plants (Jagdale and Grewal, 2004). Based on FAO-defined IPM principles, a comprehensive strategy for managing pest and disease pathogens should combine cultural, physical, biological, and chemical methods, with priority given to non-chemical approaches such as prevention, exclusion, sanitation, monitoring, forecasting, and early diagnosis to limit pest growth and establishment (FAO, 2020; ESA, 2025). Options for prevention involve cultural practices, including the use of resistant cultivars, cleaning tools, sourcing pest-free seeds or transplants, and the correct disposal of infected plants (Fig. 4). Modifying agricultural practices through the use of appropriate plant spacing, the choice of pest-resistant crop types, balanced fertilizing, or crop rotation are examples of cultural practices.

Suppression options are employed when pest populations increase to a level where they may have an adverse economic impact (e.g., yield loss or cosmetic damage). There are multiple choices when it comes to applying suppressive or curative strategies, which encompass physical, biological, and chemical approaches. Heat and cold treatments, as well as energy sources such as light traps, irradiation, light regulation, and sound, are some of the physical

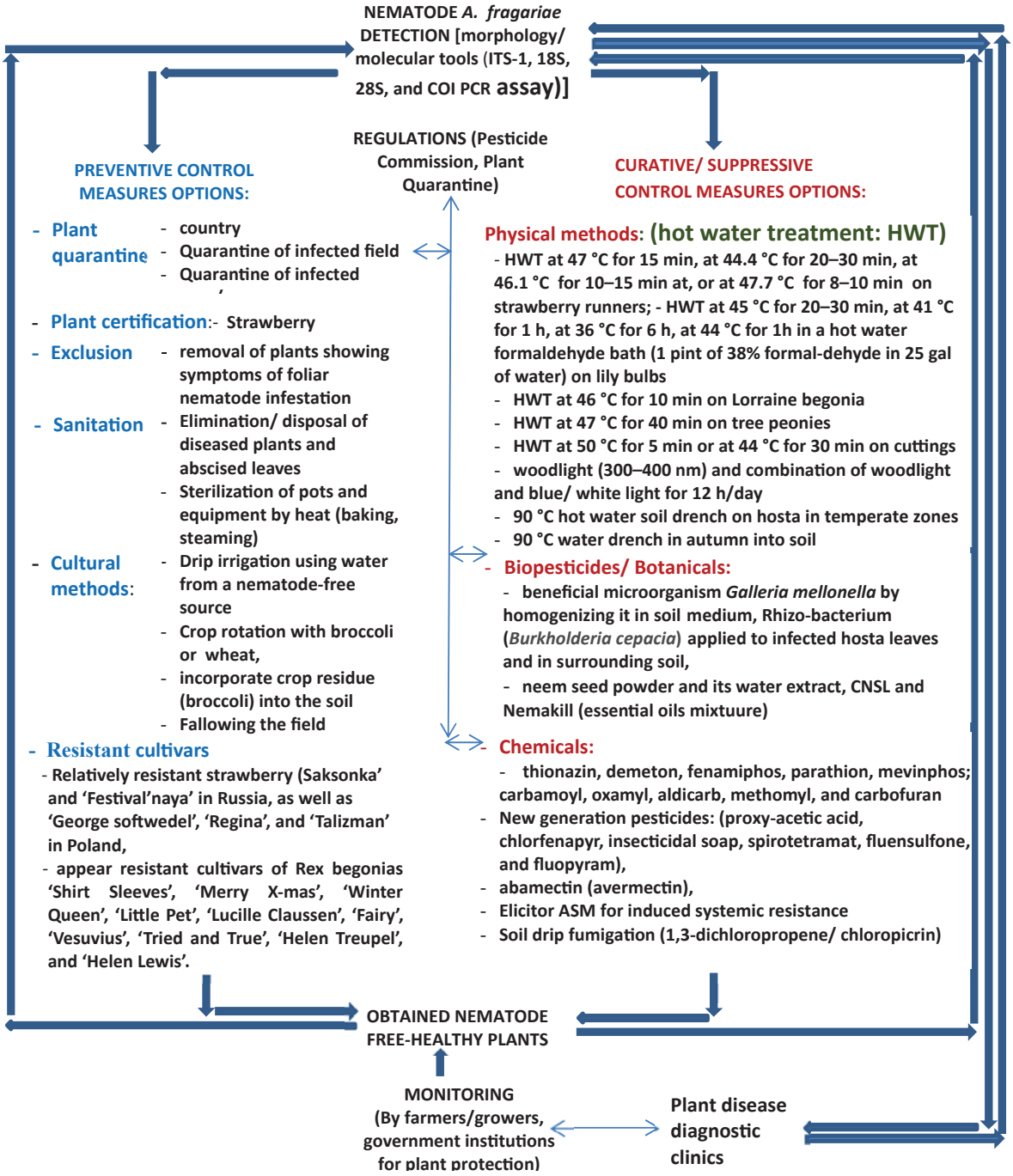

Fig. 4: The constructed diagram of the available control measures and the consultative institutions for a comprehensive approach to a safe and effective management strategy of the foliar nematode *Aphelenchoides fragariae*

approaches used to limit the spread of insect pests (Vincent *et al.*, 2003; Lal and Rohilla, 2007). The term biological control pertains to the regulation of nematode populations by employing natural adversaries of pests, which include both predators and parasites (Lahlali *et al.*, 2022). Several biological

control agents (BCAs) have been screened against *A. fragariae*; among them are *Galleria mellonella* (Jagdale and Grewal, 2008) and Rhizobacterium (*Burkholderia cepacia*) (Jagdale and Grewal, 2002). Non-fumigant and fumigant chemicals should be utilized solely when required. Some old and new generation nematicides have been investigated and proved effective against *A. fragariae*. The comprehensive strategy in the IPM of *A. fragariae* includes government involvement in nematode control to enhance the effectiveness of efforts to mitigate the spread of *A. fragariae* and ensure the safe use of nematicides.

RECOMMENDATION

This study explores and updates the bioecological characteristics data of *A. fragariae* as an invasive species, its damage and loss, its incidence in Indonesia, and its various control measures that are effective against *A. frgariae.* This document outlines essential recommendations for the safe and effective management of *A. fragariae*. The historical presence of *A. fragariae* in Indonesia could act as a cautionary tale for non-infected nations to stay alert regarding the possible risk of infestation. Recommendations for Policy makers in Indonesia, the foliar nematode should be listed as one of the major pests that could impede sustainable horticultural production and be included in the early warning system (EWS) programs for monitoring horticultular major pests. Recommendations for researchers include the evaluating and adopting a new-generation pesticides as chemical alternatives botanicals (neem, CNSL, essential oils) and biological agents (*Burkholderia cepacia*, *Galleria mellonella*) products as non-chemical alternatives for safely and effectively controlling foliar nematodes in IPM systems. This study is advantageous, particularly for local authorities or policymakers aiming to enhance their initiatives designed to boost resident involvement in the management of foliar nematode. Additional implications is for potential economic impact in Indonesia and globally.

CONCLUSION

The bioecological traits of *A. fragariae* as an invasive species include the ability to survive without a host plants, the capacity to reproduce rapidly, adapt to a broad variety of host plants, have a large capacity for dispersal, and endure a wide range of ecological and climatic conditions. As of now, it has been noted that roughly 500 plants from about 100 families are affected by this nematode. The nematode is well adapted to tropical and temperate climates, and has been reported across regions covering five continents. Significant yield loss, decreased quality, and nematode-contaminated plant seeds, seedlings, traded yield, and soils that are infested all possible outcomes of *A. fragariae* damage. The simultaneous presence of infestations and secondary pathogens can lead to more severe symptoms and a higher frequency of occurrence, which in turn results in greater economic losses, reduced yields, and infested fields. However, the damage caused by this nematode in Indonesia has not yet been assessed. However, *A. fragariae* infestation may result in a defoliation of approximately 60–80% (on king of bitter) and a decline of 65%–82% (on strawberry). On a global scale, information regarding economic losses from *A. fragariae* is quite limited, in part because of pesticide restrictions, the presence of overlapping secondary pathogen infestations, and export rejections that are related to nematode interceptions or regulatory complications. In Indonesia, since its first report in West Java (2003), this A2 quarantine pest has spread to new hosts, threatening the horticultural industry. It infects ornamentals, medicinal plants, strawberries, shallots, and garlic, reducing yield and quality. Control is contingent upon preventive and curative strategies, with multiple methods having already shown effectiveness. Preventive measures include molecular PCR diagnostics (ITS-1, 18S, 28S, COI), quarantine of pest-free areas, strawberry certification, crop rotation (broccoli–wheat) with residue incorporation, drip irrigation using clean water, and use of resistant cultivars. Curative/ suppressive options combine physical methods (hot-water treatment of runners, bulbs, cuttings and tree peonies; wood-light 300-400 nm ± blue/white light; 90°C soil water drench in autumn), biologicals (*Galleria mellonella*, *Burkholderia cepacia*, neem, CNSL, essential oils) and chemical tools. Promising chemical alternatives and elicitors include proxy-acetic acid, chlorfenapyr, insecticidal soap, spirotetramat, fluensulfone, fluopyram, abamectin and ASM, to be used only under relevant regulations. As an A2 quarantine pest, *A. fragariae* should be added to Indonesia's EWS, quarantine surveillance, and the

Directorate's technical guidelines for pest monitoring. The efficient and eco-friendly management of A. fragariae necessitates a thorough strategy that includes: 1) Developing and evaluating the IPM strategy of *A. fragariae* that includes the preventive and/or the curative/suppressive measures strategies to improve nematode management and minimize pesticide use, 2) Adopting a molecular tools for rapid and accurate detection of the nematode incidence (using the ITS-1, 18S, 28S, and COI PCR diagnostic assay), 3) Implementing available resistant varieties and/or certified planting materials, 4) Implementing an EWS through monitoring of infestations, 5) Evaluating new-generation pesticides (proxy-acetic acid, chlorfenapyr, insecticidal soap, spirotetramat, fluensulfone, fluopyram, and abamectin) as more secure chemical alternatives, 6) The evaluation of adopting biopesticides (*Burkholderia cepacia*, *Galleria mellonella*), and botanicals (neem, CNSL, essential oils) as non-chemical alternatives for environmentally safe and effective management, 7) The utilization of agrochemicals (older pesticides), particularly for curative control and soil drip fumigation, should be restricted to cases where it is required and no alternative solutions are available, in conjunction with pertinent pesticide regulations, and integrated into an IPM approach, 8) Only authorized pesticides/nematicides should be used according to any applicable regulations in the country where the grower and end user are based, 9) A strong partnership and dedicated commitment among government bodies related to plant protection programs, local governments, farmers and growers, and plant quarantine law to maintain horticultural production and quality for trade both domestically and internationally, 10) The implementation of plant quarantine regulations at both the agricultural and governmental tiers plays a crucial role in curbing the spread of nematodes and in establishing quarantines for areas free of these pests, 11) Developing AI-based early detection methods to identify asymptomatic infections and ensure healthy seedlings.

AUTHOR CONTRIBUTIONS

S.R. Djiwanti designed and conceptualized the outline of the review, searched the relevant bibliography, drafted the initial manuscript, assessed the discussion, and formulated the conclusion. Sukamto assisted in interprating data, reviewed the whole manuscript, edited the draft, and helped strengthen the final manuscript version. K.D. Sutanto helped clarify the study's conclusions, involved in drawing insights from the results, contributed to editing and enhancing the manuscript, and suggested improvements to the manuscript's quality. Miftakhurohmah and S. Puspitodjati contributed in gathering data and bibliography, contributed the opinions in discussion as well as the manuscript's final review. S. Hardiyanti and M.P. Sari contributed in prepared the manuscript regarding the manuscript format as well as the research flow. T. Widowati and P. Maris contributed in editing the final revised manuscript version, and helped in analyzing and coding the proper references. A. Nurawan helped in gathering data, synthesizing and analyzing the collected data.

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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.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Per cent
°C	Degree Celcius
°F	Degree Fahrenheit
min	Minute
h/day	Hour/day
A2	A quarantine pest category classification which includes plant pests that have become established in a country (i.e. Indonesia), but which remain isolated to certain areas in a country
ASM	acibenzolar-S-methyl
BBKP	Balai besar karantina pertania/ Agriculture Quarantine Major Service
BCAs	Biological control agents
BRIN	Badan Riset dan Inovasi Nasional (National Research and Innovation Agency)
CABI	Commonwealth Agricultural Bureaux International
CNSL	Cashew nut shell liquid. Dinas Komunikasi dan Informatika Provinsi Jawa Timur (East Java Province Communication and Informatics Office)
e.g.	Exempli gratia/for example
Diskominfo Jatim	Dinas Komunikasi dan Informatika Provinsi Jawa Timur (East Java Province Communication and Informatics Office)
Dit. PTP	Direkttorat Perlindungan Tanaman Pangan (Directorate of Food Crop Protection)
EPA	Environmental Protection Agency
EPPO	European and Mediterranean Plant Protection Organization
ESA	Entomological Society of America
EWS	Early warning system
FAO	Food and Agriculture Organization
Fig.	Figure
HWT	Hot water treatment
IPM	Integrated pest management
IPPC	International Plant Protection Convention
ISR	Induced systemic resistance
Kemendag	Kementerian Perdagangan Republik Indonesia (Indonesian Ministry of Trade)
Kementan	Kementerian Pertanian Republik Indonesia (Indonesian Ministry of Agriculture)
nm	nanometer
NGP	New generation pesticides
mm	millimeters
PCR	Polymerase chain reacion
PGPR	Plant growth-promoting rhizobacteria
rRNA	Ribosomal ribonucleic acid
rDNA	Ribosomal deoxyribonucleic acid
PCR	Polymerase chain reaction
UC IPM	University of California Integrated Pest Management
USD	United States dollar
USDA	United States Department of Agriclture
US EPA	United States of Environmental Protection Agency
WHO	World Health Organization

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